Co-Optimized Multi-Mode Light-Duty Vehicle Engine

Annual Merit Review – 2020

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Hyundai-Kia America Technical Center Inc.

June 4, 2020

Project ID: ft087
Award #: DE-EE0008478

Michigan Tech

HYUNDAI
Multi-Mode GCI

OVERVIEW

Timeline

- Start date: 1/2/2019
- End date: 5/30/2022
- 30% Complete

Budget

- Total Funding for 3 years
- $2.17M Federal-Share
- $2.78M Cost-Share (56%)
- $4.95M Total Project Budget
- Funding for FY19: $944,108
- Funds Anticipated FY20: $817,802

Project Partners

- US Dept of Energy-VTO
- Michigan Tech University
- Phillips 66
- Project Lead: Hyundai

Barriers

- Co-optimizing novel gasoline blendstock fuel specification with GCI combustion system needed to maximize efficiency potential
- Gasoline CI fundamentals are not well understood. Improved fuel properties and chemistry models are needed to develop combustion system
- Advanced Combustion System hardware are needed to cover multi-mode operation range.
- Multi-mode engine operation requires mode switching strategy thus advanced controller will require strategy with 3 modes

RELEVANCE

- To meet 2025 VTO goals for 10% improved in vehicle fuel economy, an advanced multi-mode (SI+GCI) combustion system is being co-optimized with gasoline fuel for LD vehicle.

- Using widely available gasoline blendstocks in the US, ensure US energy independence into the future. Can be blended with bio-renewable fuels (ie. E30)

- Challenges to apply GCI technology to LD passenger car engine.
  - Maintaining low-load reactivity to ensure stability.
  - Managing high load max pressure rise rates to < 8bar/deg over the range of
  - Meeting exhaust temp limits at peak power conditions

- Extensive CFD modeling needed:
  - Development of real fuel chemistry and fuel properties models are needed
  - improve GCI combustion fundamental understanding and for performance operation
  - Combustion system hardware procurement (HP DI Fuel sys., advanced boosting, etc)

Advanced engine controller required to do:
- multi-mode operation and mode switching.
- Prediction of in-cylinder conditions (temp, residuals) needed to ensure combustion robustness, prior to and during mode switch events.

Objectives:
- Hyundai to develop a co-optimized fuel and multi-mode SI + (GCI) engine combustion system that can achieve 15% vehicle fuel economy improvements.

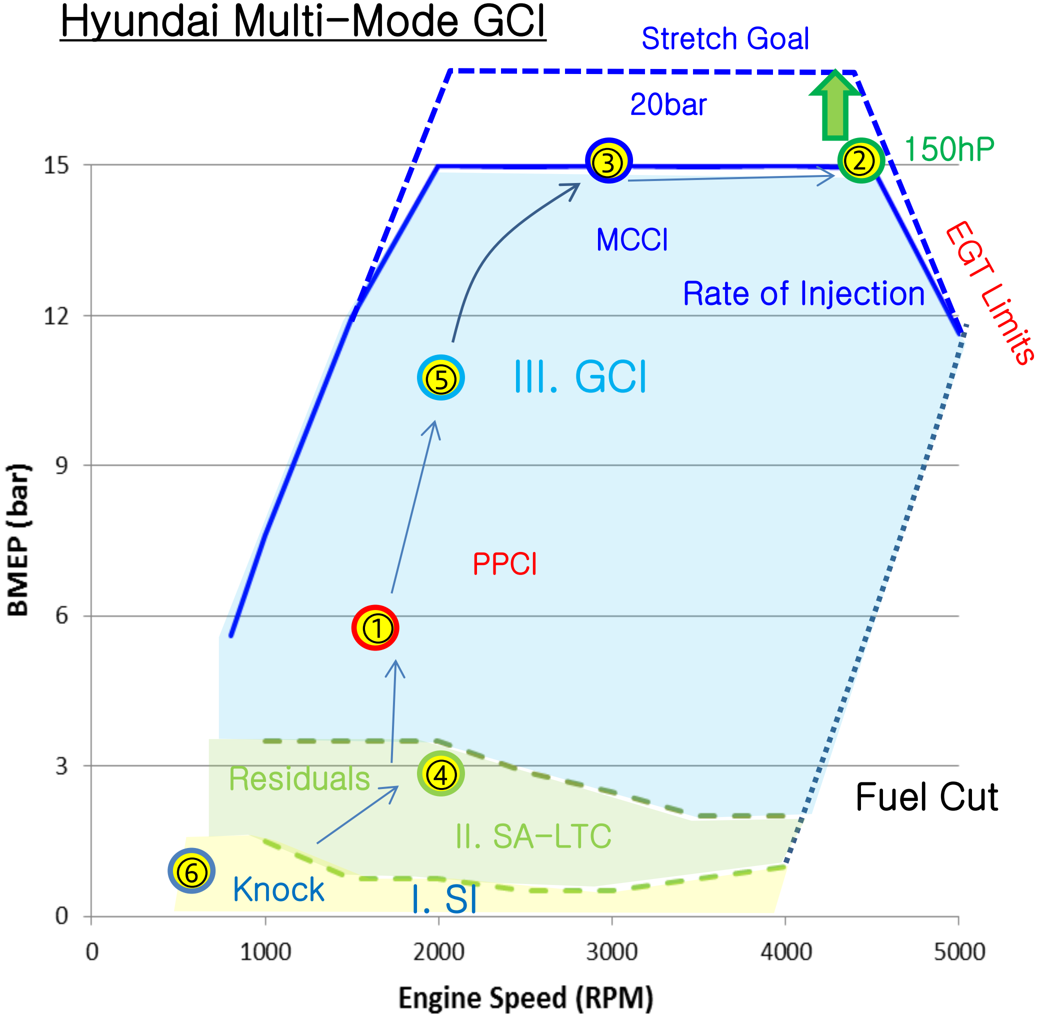
MILESTONES

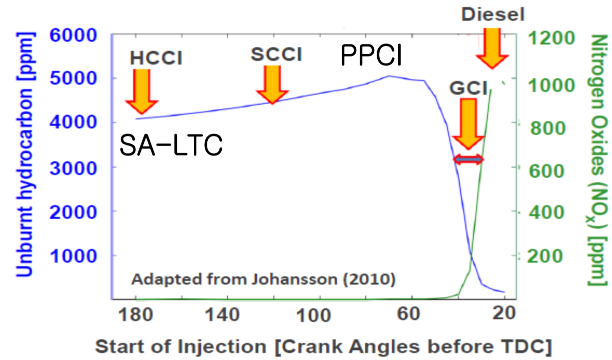
Month/Year	Description of Milestone	Status	R/Y/G
Aug 2019	M1.1 Technical Specification comprised of 0D boundary condition & analysis based on torque curve of proposed multi-mode capable eng	Complete	
December 2019	M1.2 CFD Model build. 3D model construction to conduct predictive multi-mode combustion & provide feedback to hardware design.	Complete	
June 2020	M1.3 Fuels formulation selection and justification of down-selected fuel for GCI testing, -Advanced CI Merit function	In-Process (Moving to Year 2)	
March 2020	M1.4 Steady-state “Mule” Engine testing of multi-mode and BSFC demo. LTC and GCI mid to high load are on target	Complete	
May 2020	M1.5 Go/No Go: High confidence multi-mode engine hardware able to meet program targets of 150hP and at least 15% in simulated FTP75 fuel economy over baseline.	On-Schedule	
December 2020	M2.1 Adaptive mode-switch controller setup & validated on hardwar e-in-the-loop bench.	Ahead of Schedule (Year 2 goal)	

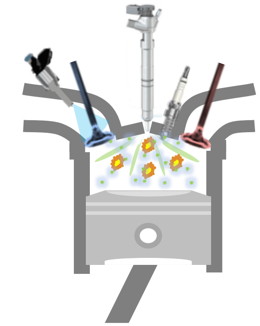
Summary: Project was delayed 5 months due to contracts negotiations, but critical controls item from year 2 was pulled forward into Year 1 and used to control multi-cylinder GCI engine to meet 15% target. Overall, th e projest is well on track.

TECHNICAL APPROACH

Hyundai Multi-Mode GCI



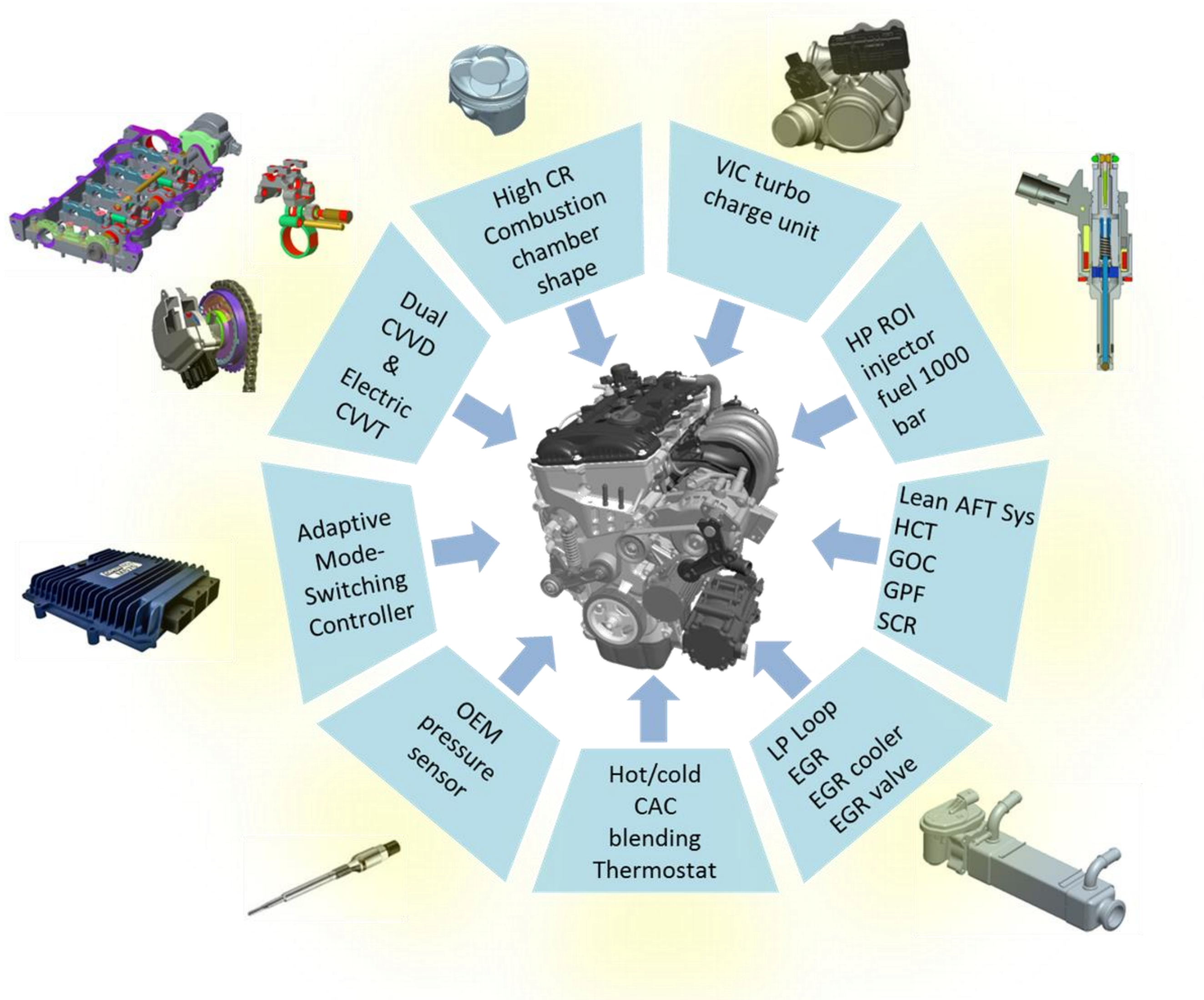




- Specification multi-mode hardware to meet targets
  - Valve-train to drive residuals for SA-LTC
  - High Pressure Late Direct-Injection for GCI
  - Central Spark & Ignition system
  - Boost & EGR Systems to support above
- 3D combustion CFD model, study the Fuel Effects o n GCI combustion modes (LTC & MCCI)
- Selection of fuel matrix & development of Advanced CI merit function.
- Advanced engine controller capable of executing combustion mode-switch
- Demonstration of GCI operation on multi-cylinder

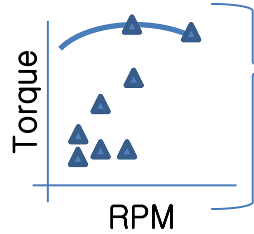
Project Goal: 15% fuel economy improvement over SI engine baseline on a simulated FTP 75 cycle. Engine must also achieves 150hP and have a useable torque curve.

MULTI-MODE COMBUSTION SYSTEM ENABLERS

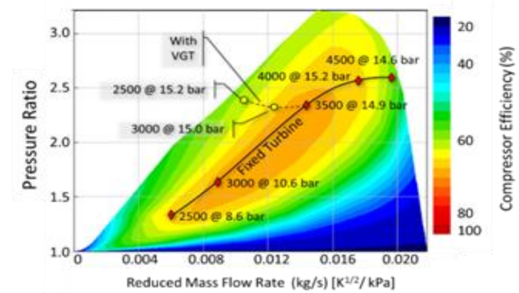


M1.1. Technical Specs Completed. Key Enablers defined to explore fuels and GCI combustion modes.

TECHNICAL ACCOMPLISHMENTS AND PROGRESS



Engine Performance Targets



Technical Specifications (0D Engine Model)
Boundary Conditions

1D GTDrive Model
FTP75 Cycle Simulation

1D GTPower Model
Boost, EGR, CAC/CAH

Define/ Refine

1D Model

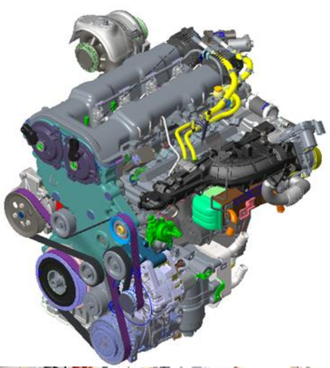
Fuels & Chemistry

3D CFD

Design

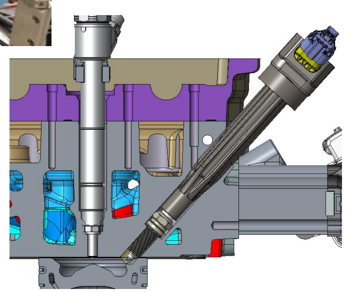
Engine Testing

Validation



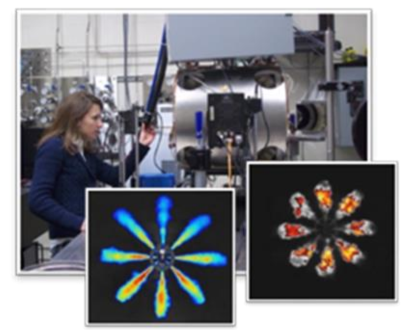
MCTE Testing of Multi–Mode
4cyl Combustion Perf. & Emissions

Multi–Mode Engine Controller
1cyl Combustion Perf. & Emissions



Combustion Sys Hardware Design
Cyl head, piston, injector, turbo,

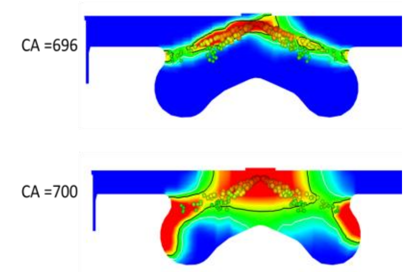
3D CFD Converge
Combustion Recipe Injector, TKE, EGR



Fuel Spray & CV Chamber Work
ROI, Penetration, Vaporization

Fuel Formulation Selection
Reduced Surrogate Mechanism Dev
Adv GCI Merit Function

Fuels



REAL FUEL MODELING

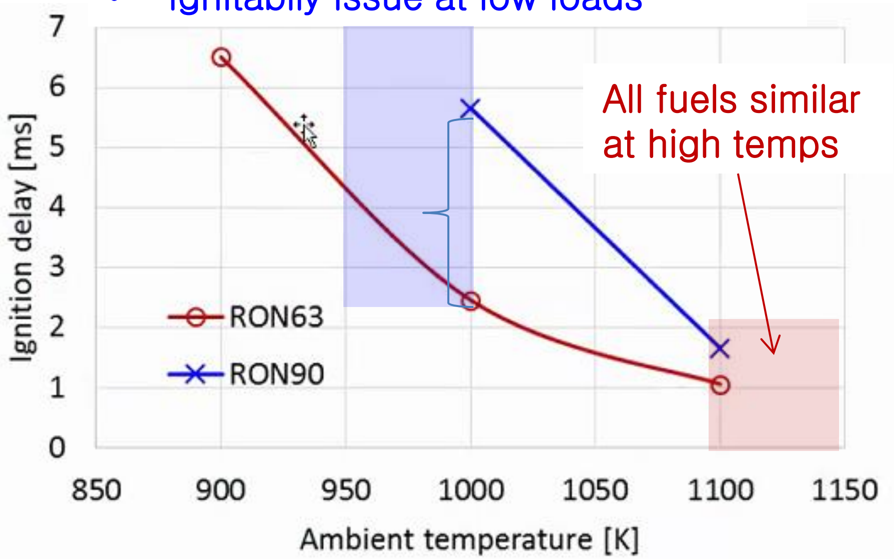
PHILLIPS 66 | Michigan Tech | HYUNDAI Multi-Mode GCI

- 4 Fuels selected with RON of 63, 71, 80, & 90
- Fuel property experiments Dr. Yu Shi (Phillips 66)
- Real Fuel Surrogate Chem by Prof. Y. Ra (MTU)
- Prediction of ignition delay & distillation complete
- SAE Publication 2020-01-0784
  - "Real Fuel Modeling for Gasoline Compression Ignition Engine"

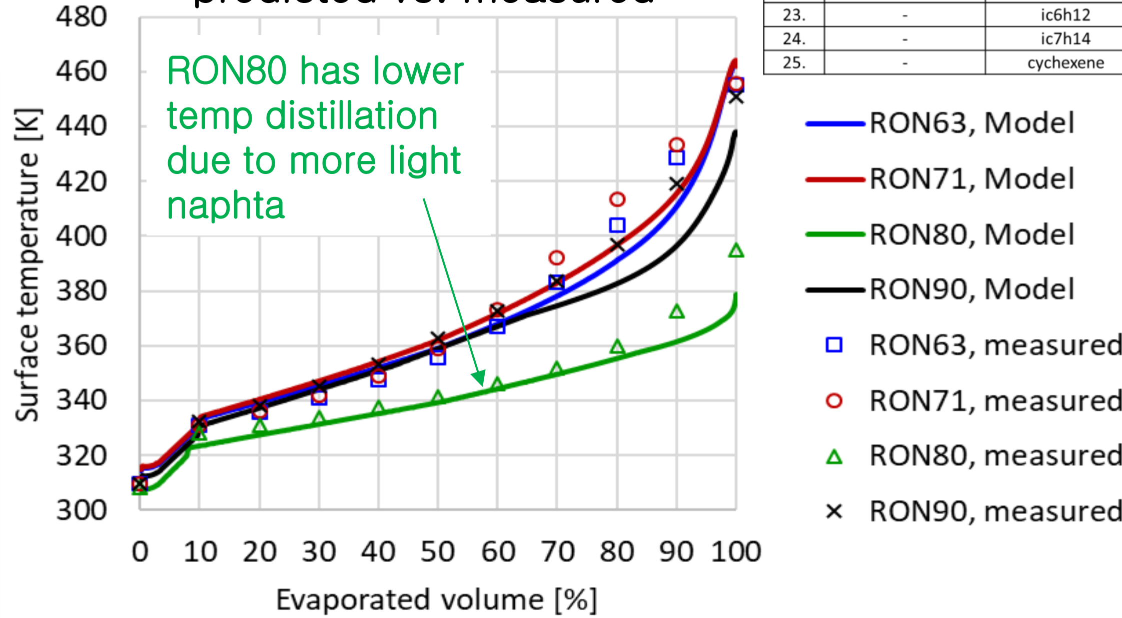
NO.	RON 63 (22 Component)	RON 90 (25 Component)
1.	ic8h18	ic8h18
2.	c4h10	c4h10
3.	ic5h12	ic5h12
4.	ic6h14	ic6h14
5.	ic7h16	ic7h16
6.	toluene	toluene
7.	c9h20	ic9h12
8.	ic9h12	chx
9.	c10h22	nc5h12
10.	chx	nc7h16
11.	nc5h12	c6h6
12.	nc7h16	mch
13.	mch	c6h5c2h5
14.	c10h18	mcymene
15.	c8h18	nc6h14
16.	c6h5c2h5	c5h10
17.	mcymene	c6h12
18.	c11h16	cpt
19.	nc6h14	dmchx
20.	dmchx	ic10h22
21.	ic10h22	ic9h20
22.	ic9h20	ic5h10
23.	-	ic6h12
24.	-	ic7h14
25.	-	cychexene

Predicted ignition delay

- RON90 longer delays at low temps
- Ignitabily issue at low loads



Distillation curves: predicted vs. measured



M1.3: Surrogate fuel models predict fuel distillation. RON91 Fuel will have issues igniting at low temps.

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3D CFD COMBUSTION MODEL

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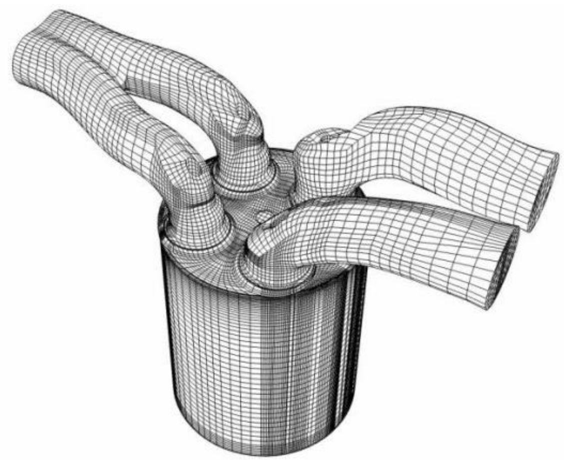
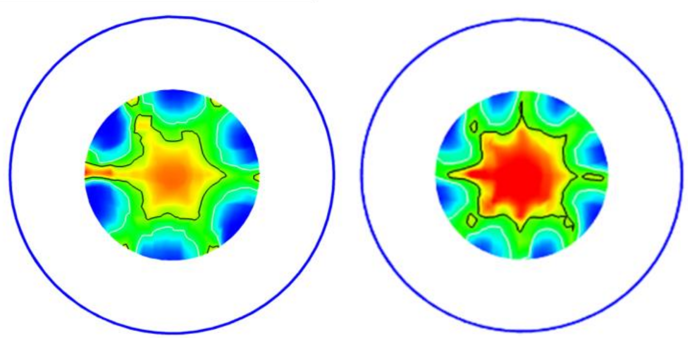
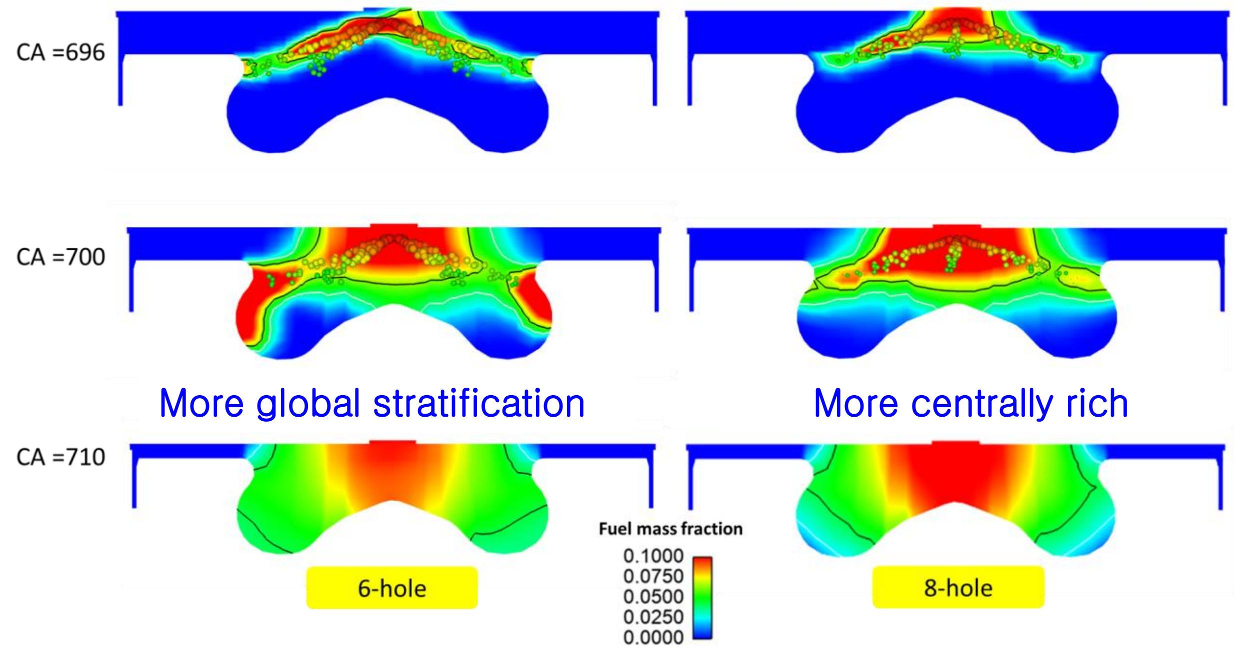
Multi-Mode GCI

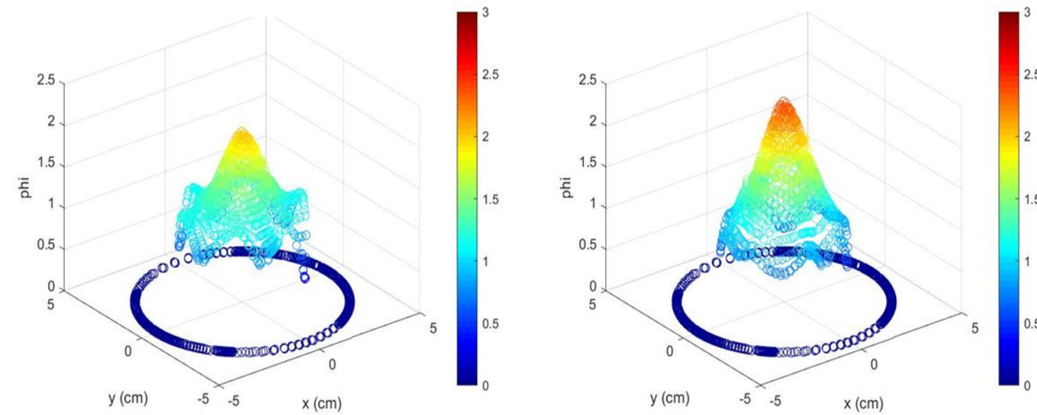
- KIVAv4 CFD results
- Engine Speed: 1500rpm
- Load: 13bar BMEP
- Conventional CI Bowl
- 6 hole vs 8 hole
- Strategy: MCCI exploration





6-hole 8-hole





6-hole 8-hole

M1.2: 3D CFD Model has been built. 6 hole DI more suitable for GCI bc better overall global stratification

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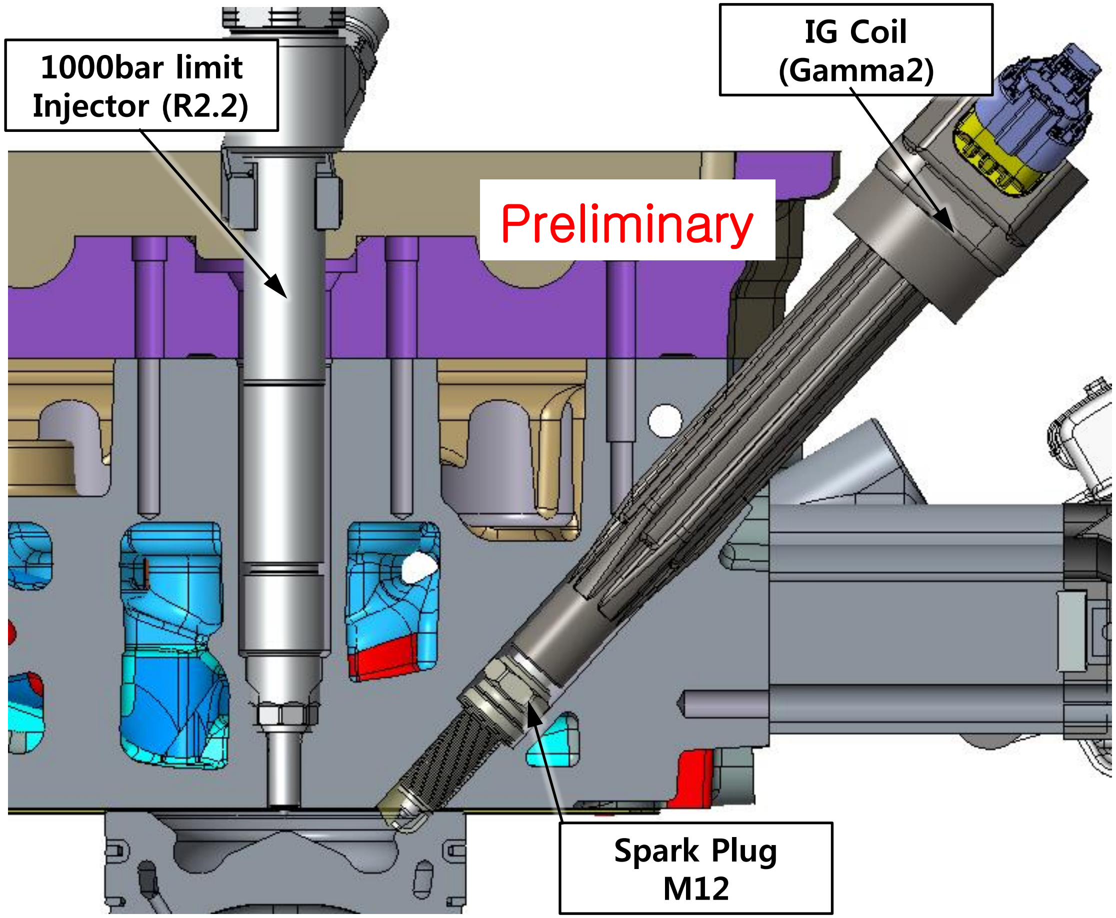
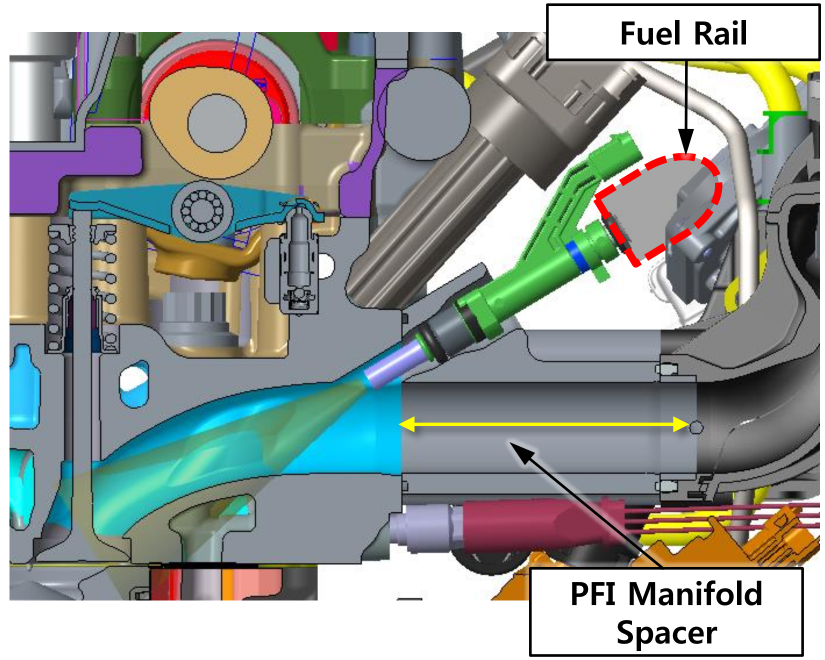
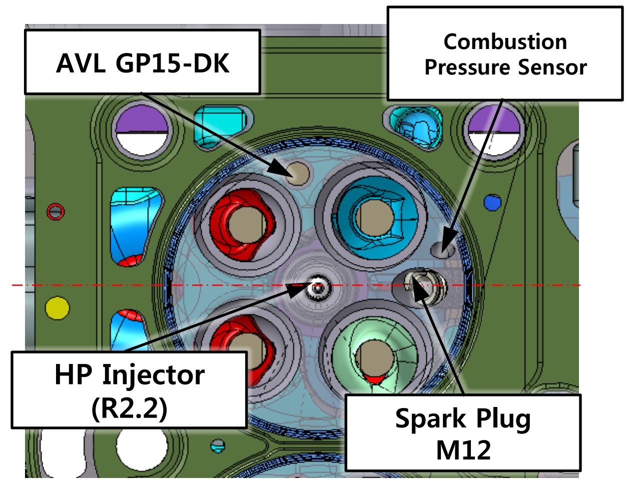
MULTI-MODE GCI COMBUSTION SYSTEM

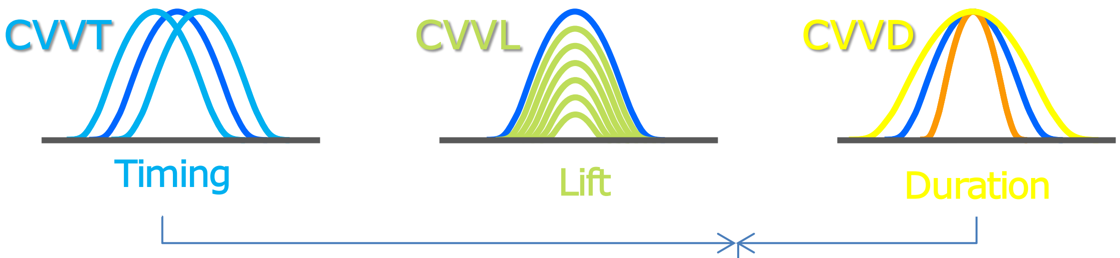


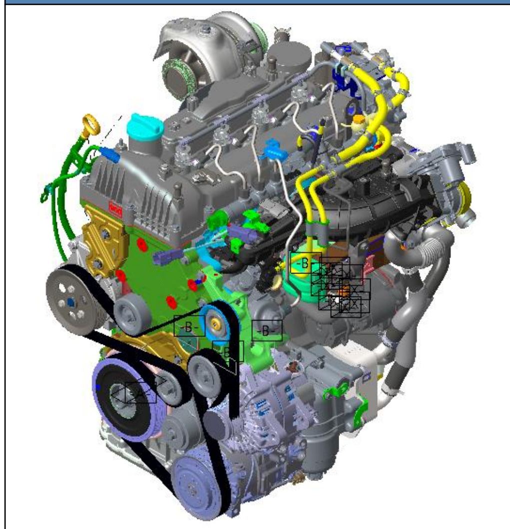
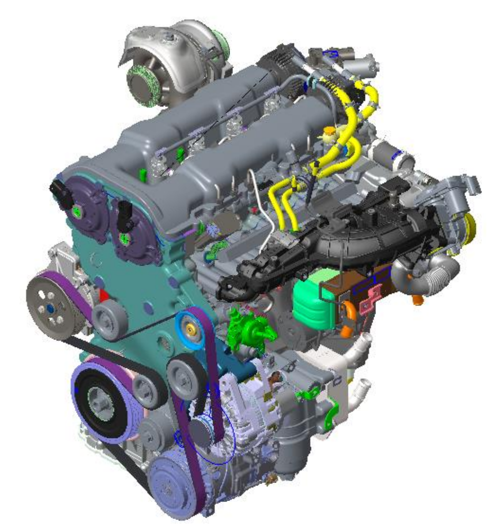


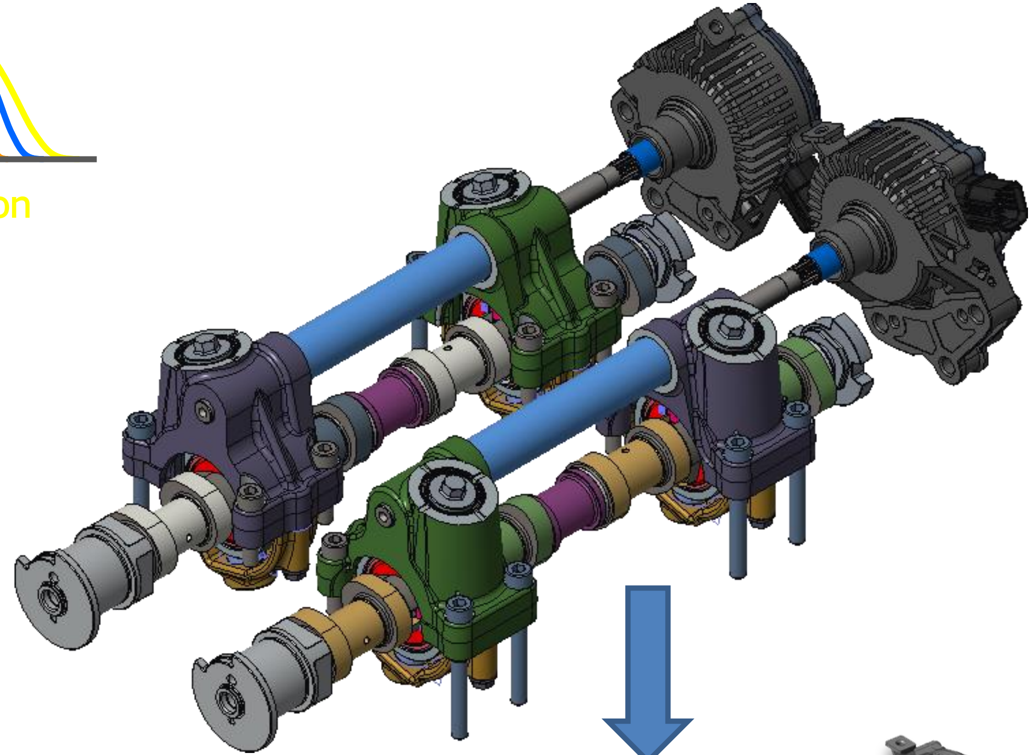


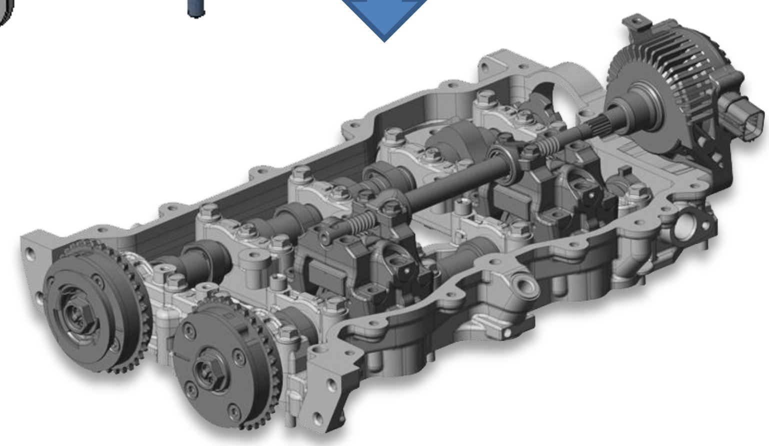
M1.1. Technical Specs Completed. Key Enablers defined to explore fuels and GCI combustion modes.

HYUNDAI DUAL CVVD+CVVT VALVETRAIN



R 2.2L Base Engine	GCI_01_B1 2.2L CVVD
	

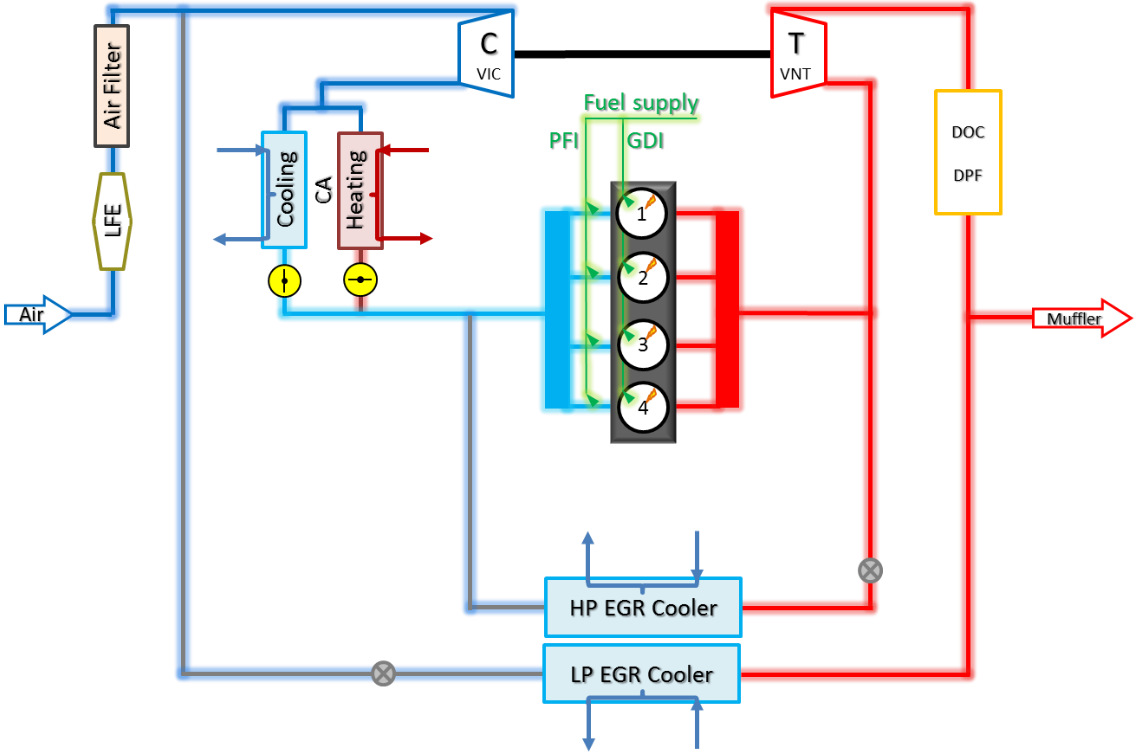


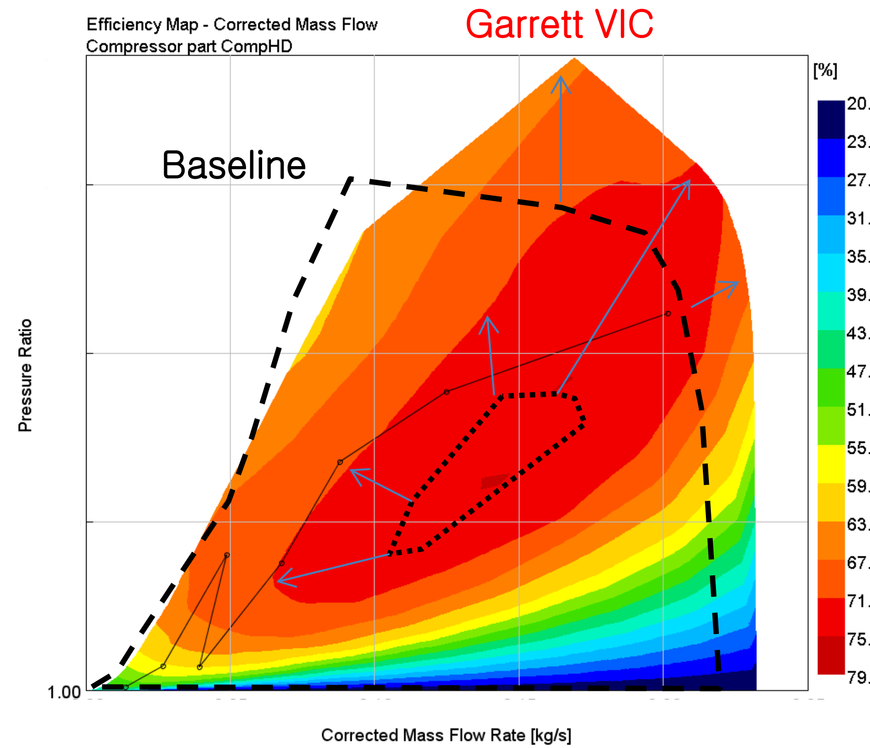


- Base Engine has only conventional VT
- New engine will have Dual CVVD & CVVT (both intake and Exhaust)
- Will enable Negative Valve Overlap, precise residual control.
- Key enabler for SA-LTC mode

Hyundai Dual CVVD + CVVT systems combined to enable advanced valvetrain strategies (NVO, ATK, etc)

AIR SYSTEM (TURBOCHARGER SPECIFICATION)





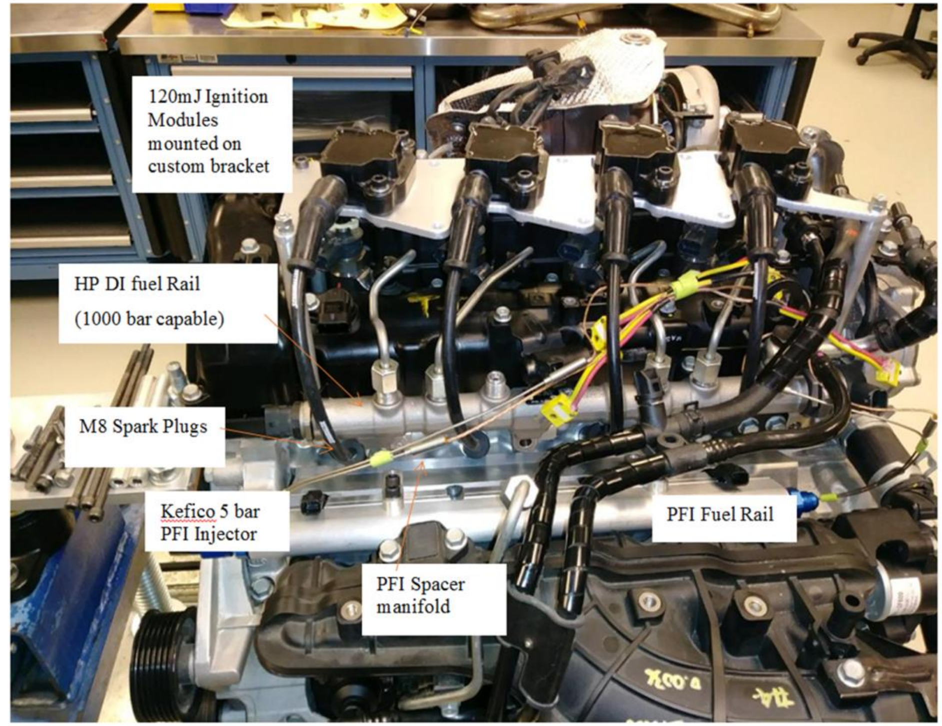
- Garrett-Motion provided Variable Inlet Compressor (VIC) technology. Offers a wider flow range and higher pressure ratio, and significantly larger high efficiency island (79%) versus baseline turbo spec.
- Additionally the turbine exhaust gas temp limit was increased to 860degC.
- The map is well equipped to be able to handle flow requirements at high power and low flow high pressure points for fuel economy and torque

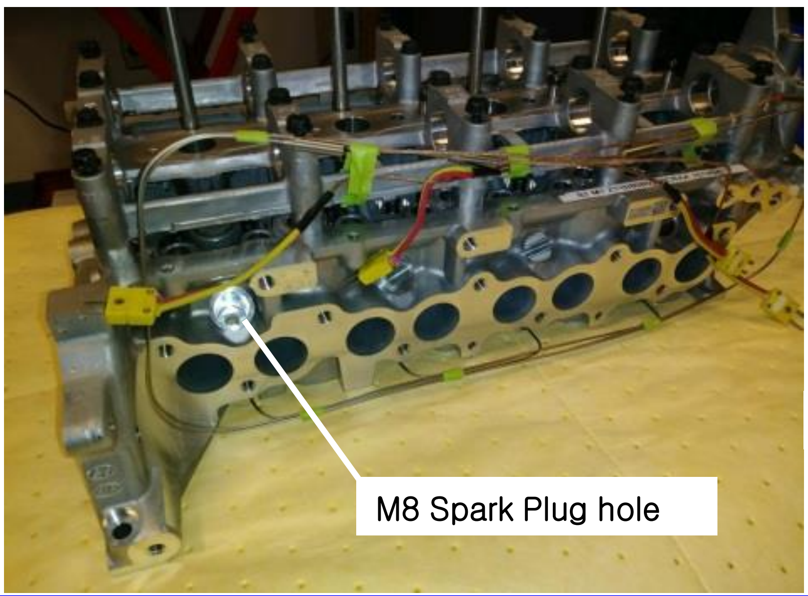
VIC turbo: larger high efficiency island, wider flow range as well as higher PR>3.0 in a single stage

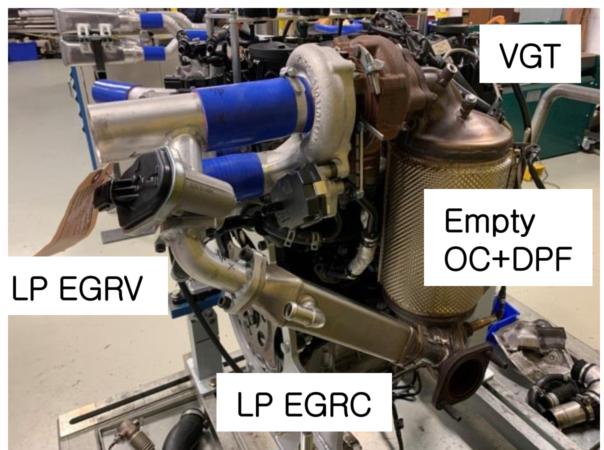
MULTI-MODE GCI_01 ENGINE BUILD

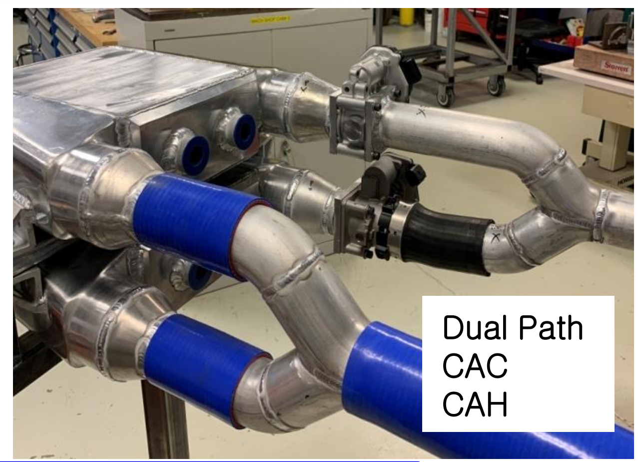
Hyundai Multi-Mode GCI Gen 1 (GCI_01_B1)

- Pmax: 180bar
- Central DI, and bowl in piston design
- DI Fuel Pressure: 1000bar
- PFI injection system: 5bar
- 120mJ Spark Ignition System
- Dual Loop EGR (HP&LP)
- Dual Path Charge Air Heating and Cooling
- VGT Turbocharger (PR>3.0)
- Can explore GC I (PPCI/MCCI) & SI
- No DUAL CVVD+CVVT Valvetrain
    - Will be added to (GCI_02)









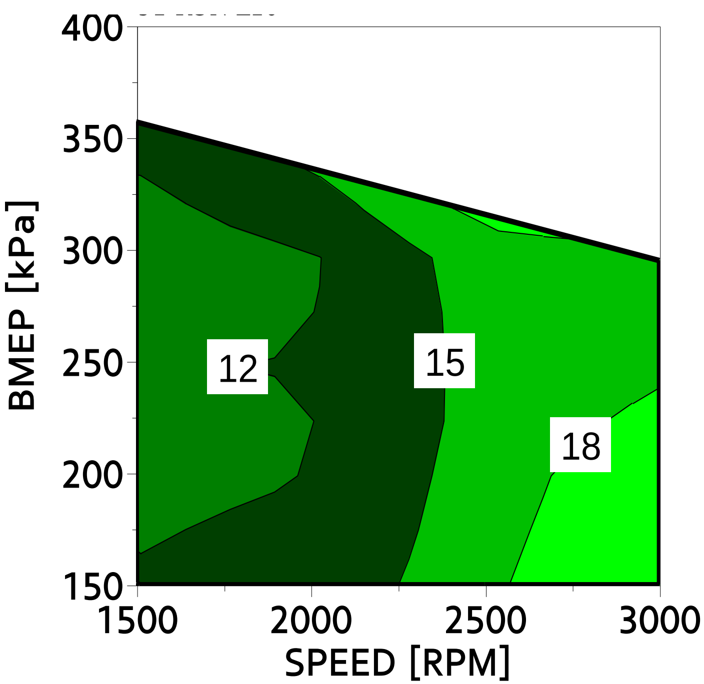
1st Generation Multi-Mode GCI engine designed to explore GCI and SI modes only. Build Complete

MULTI-CYLINDER ENGINE - SA LTC (HCCI) MODE

- Spark-assisted low temperature combustion (SA-LTC)
- Demonstrated at HATCI using 2L CVVD CR14
- Key Enabler: Dual (Int/Exh CVVD & CVVT) actuator setup.
- RON 91 E10 Gasoline Fuel was used.

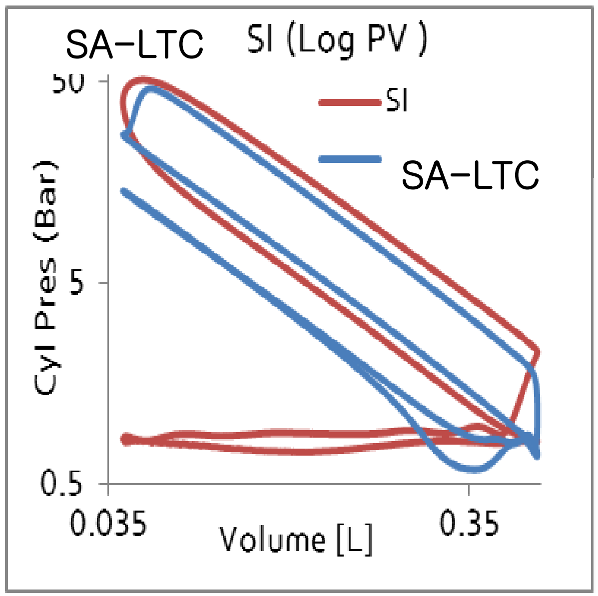
2L Dual CVVD+CVVT

Δ Fuel Consumption %

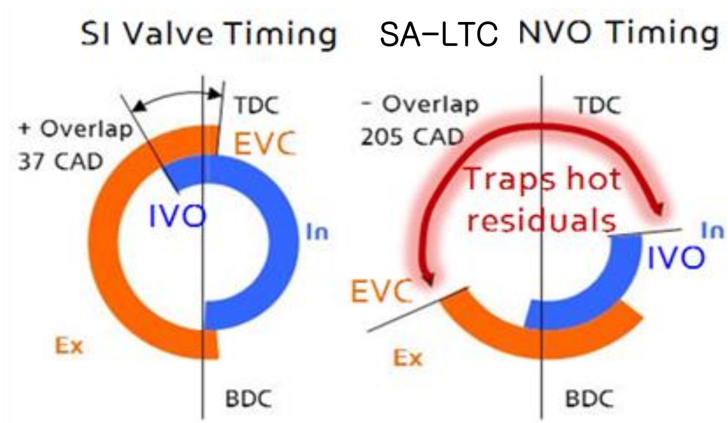


12-18% Improvement in BSFC versus SI mode

SI vs LTC Mode



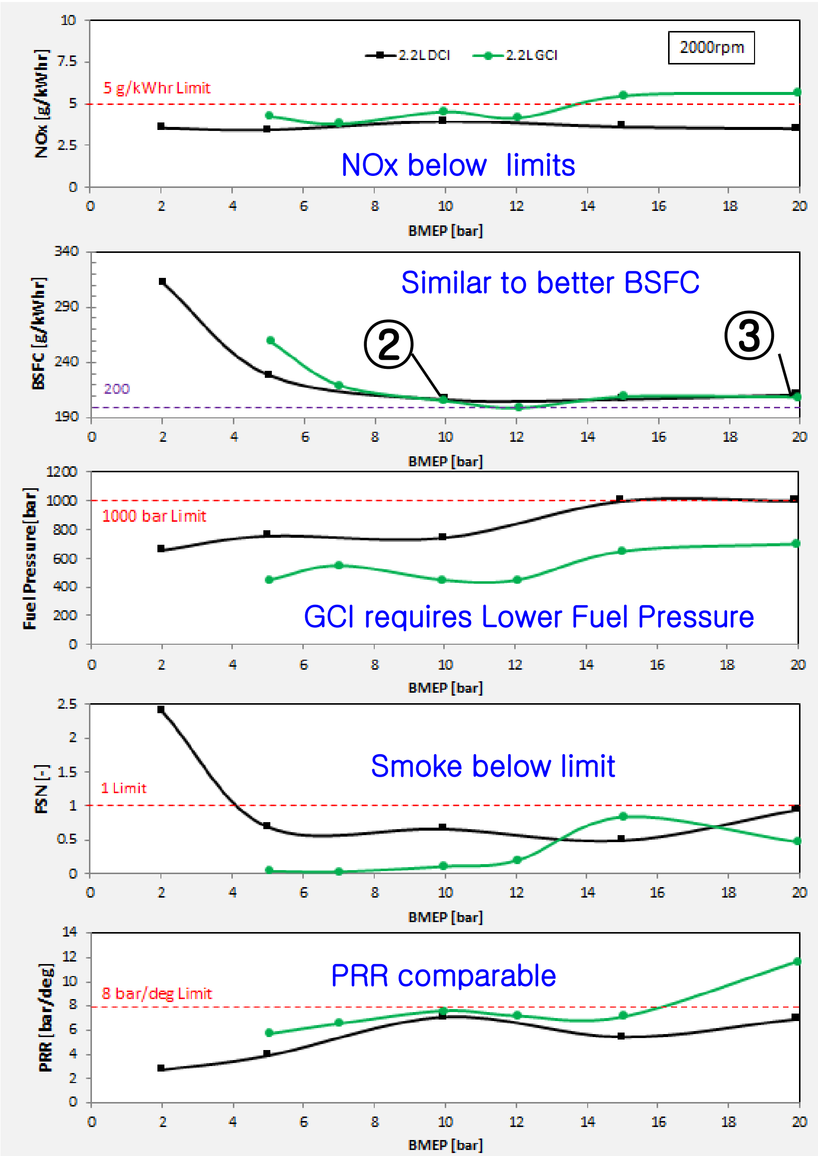
NVO Gas Exchange and Rapid HCCI Pressure Rise

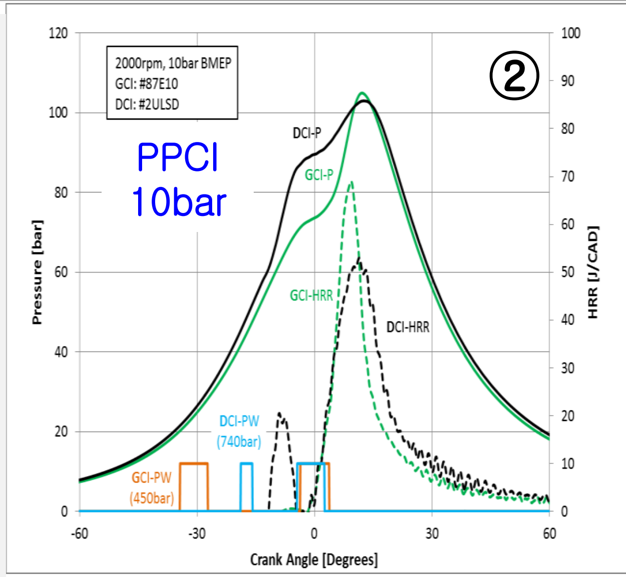


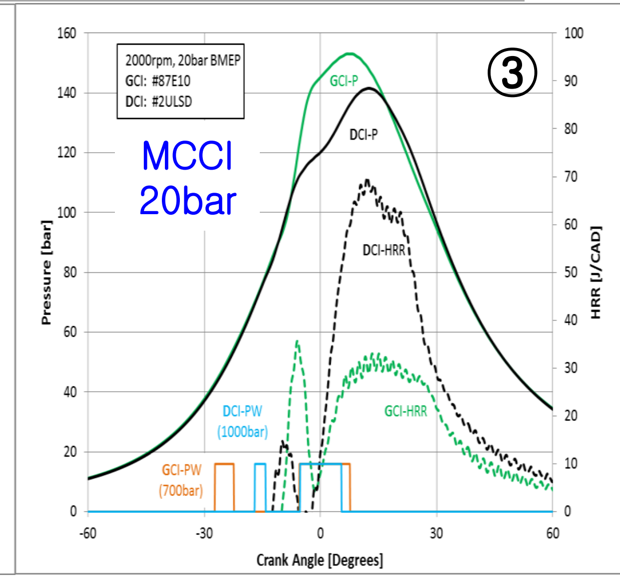
Dual CVVD+CVVT enables NVO

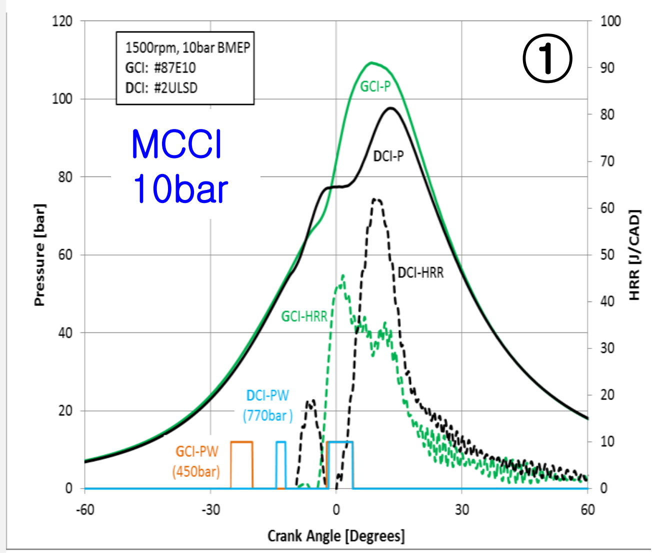
NVO used to enable SA-LTC in early 2019 using 2L with Dual CVVD + Dual CVVT system. 18% BSFC↑

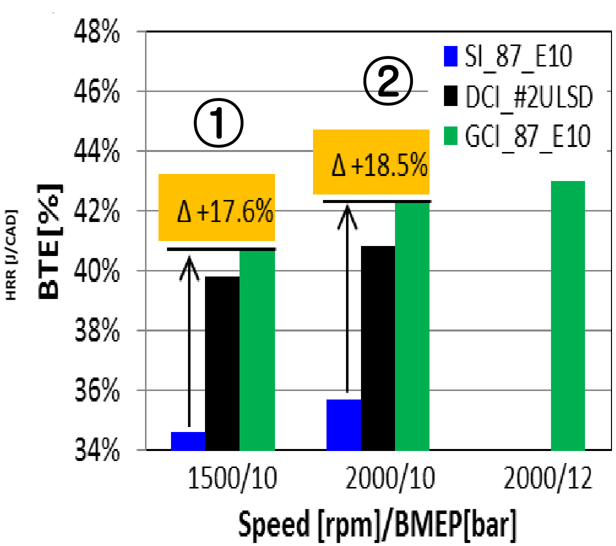
MULTI-CYLINDER ENGINE - GCI MODE











- RON 91 E10 Gasoline Fuel was used.

GCI achieved peak BTE 43% without optimization. △BTE +17.5%to 18.5% versus SI BSL.

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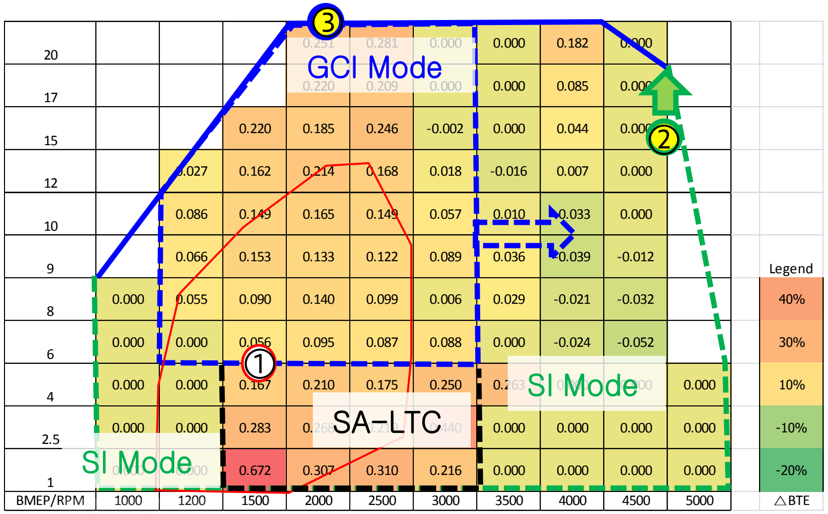
BRAKE THERMAL EFFICIENCY BENCHMARKING

HYUNDAI Multi-Mode GCI

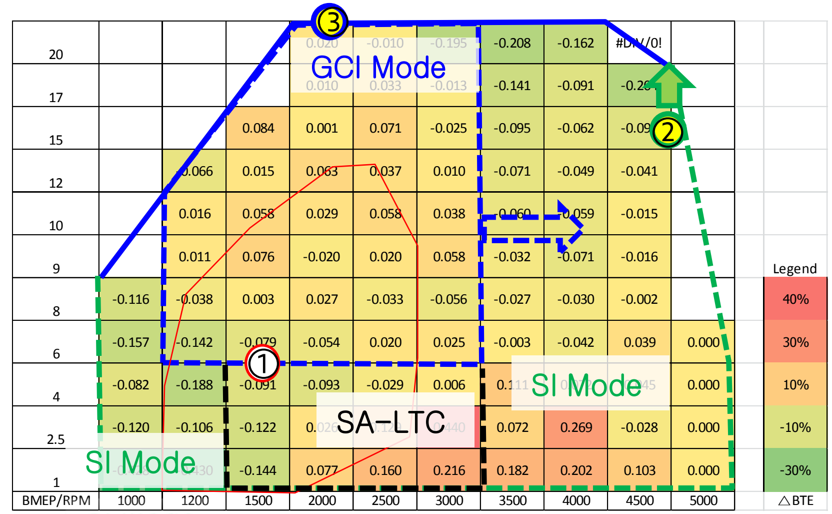
FTP Cycle
Power Target
Torque Curve

HATCI Multi-Mode GCI vs SI



Range	1500 to 3000 RPM
Avg BTE gain	Delta 17.5% (GCI v SI)

HATCI Multi-Mode GCI vs DCI

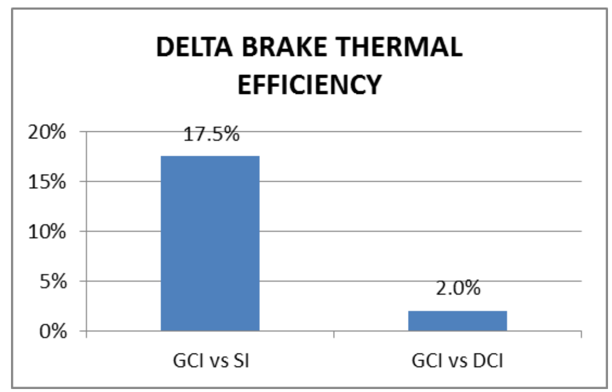


Range	1500 to 3000 RPM
Avg BTE gain	Delta 2.0% (GCI v DCI)

- From1500 to 3000 rpm range, Multi-mode 2.2L GCI (SI, SA-LTC, GCI) modes resulted in a delta BTE improvement of 17.5% over the 2L SI baseline engine. Easily achieving 15% target for project

- Results compared to 2.2L diesel engine benchmark
- the 2.2L Multi-mode GCI resulted in a 2% improvement.

- Hyundai Multi-mode GCI is better than diesel!



Milestone Achievement: Delta BTE of 17.5% versus SI BSL and a delta BTE of 2% versus DCI

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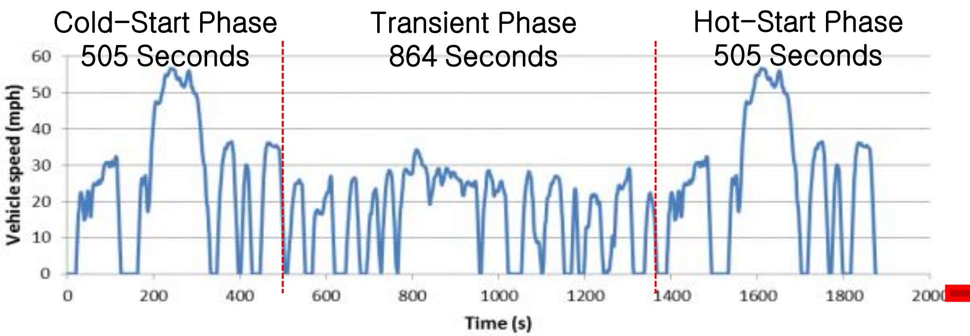
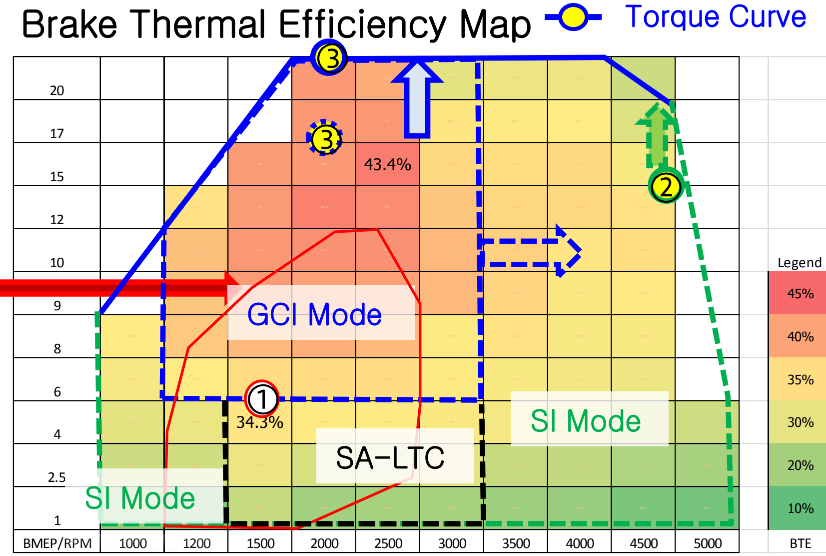
VEHICLE FUEL ECONOMY SIMULATION

FTP75 Cycle



Duration: 1874 s; Distance: 11.04 miles, Avg Speed: 21.2 mph, Max Speed: 56.7 mph

HYUNDAI Multi–Mode GCI



Vehicle Targets:

OP1: FTP Cycle

15% Fuel Economy imp
ULEV70 Tailpipe Out
Cold–starts @ –20C

OP2: Rated Power

Specific Power: >150hP
>15 bar BMEP at 4500 rpm

OP3: Torque Curve

Useable Torque Curve
12 to 20 bar BMEP
1500 to 3000 rpm

Target Vehicle:

Hyundai Tucson ULEV125
114,735 units/year total

Range	1500 to 3000 RPM
GCI Mode	Peak BTE 43.4%
SA–LTC Mode	Peak BTE 34.4%
Rated Power	Tracking >150hP @ 4500 rpm

- Multiple engine data sets combined. 1 BTE Map to predict Multi–mode result.
  - SI Mode (2L SI Baseline Data MY 2015 production)
  - SA–LTC mode (2L CVVD Engine 2019 test data)
  - GCI mode (2.2L GCI data 2020 test data)
- Resultant BTE map above will be used as input to the GTDrive Vehicle Fuel Economy Model and Compared with 2L SI Baseline
- Vehicle drive cycle using 1D GTDrive –to be completed.

GCI achieved peak BTE 43% @ 2500rpm 15bar BMEP without optimization. SA–LTC peak 34.3%

RESPONSES TO PREVIOUS YEARS COMMENTS

No presentation in 2019

COLLABORATION AND COORDINATION WITH OTHERS

Organization	Role
Hyundai America Technical Center Inc.	Lead org, base engine, 1D simulation, engine testing, combustion, controls & calibration E10 fuel testing
Michigan Technological University	3D CFD Model build SCRE and S&CV chamber testing Advanced Control estimators Fuels & GCI study
Phillips 66	Fuel formulation development & research fuel supply
Garrett-Motion	Turbocharger supply
HMETC	DI Injector characterization & supply Validation
WM International Engineering	Multi-mode base controller development Cylinder pressure feedback system
Argonne National Lab	CI Merit function development

REMAINING TECHNICAL CHALLENGES & BARRIERS

Barriers:

- Managing Pressure Rise Rates < 8bar/deg at high loads ①
  Increased smoke as speed is increased ②
- Increased EGT as combustion duration increases with engine speed ③

- All require High ROI DI fuel injector and pump for gasoline fuel. Current pump has limitation of 740bar pressure before cavitation is excessive. ④

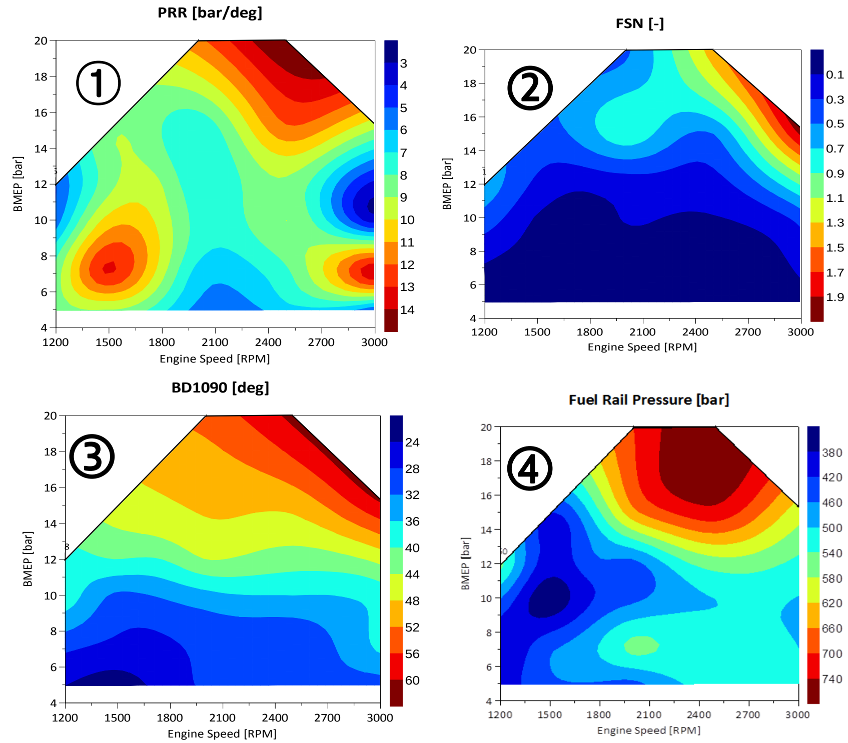
Challenges:

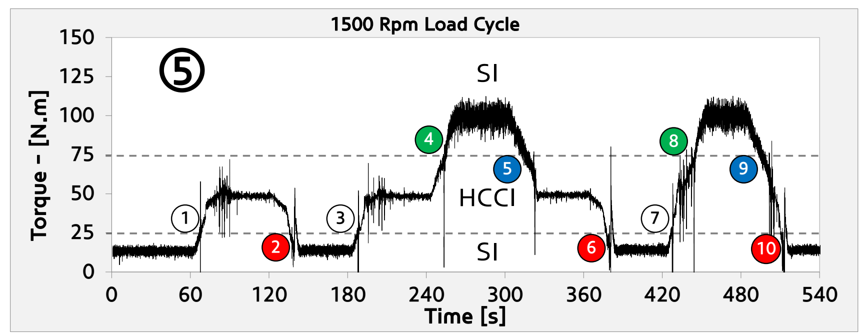
- Obtaining custom DI nozzle configurations
- Procuring 1000bar Gasoline pump that is production intent
- Completing the design and procurement of the Dual CVVD + CVVT cylinder head with central mound DI and Spark

- GCI mode low load operation extension
- SA-LTC mode operating range extension

- Development of in-cylinder condition estimators
- Development of mode-switch procedure and algorithm to eliminate torque drops ⑤

- Determine Lean Nox aftertreatment assumptions

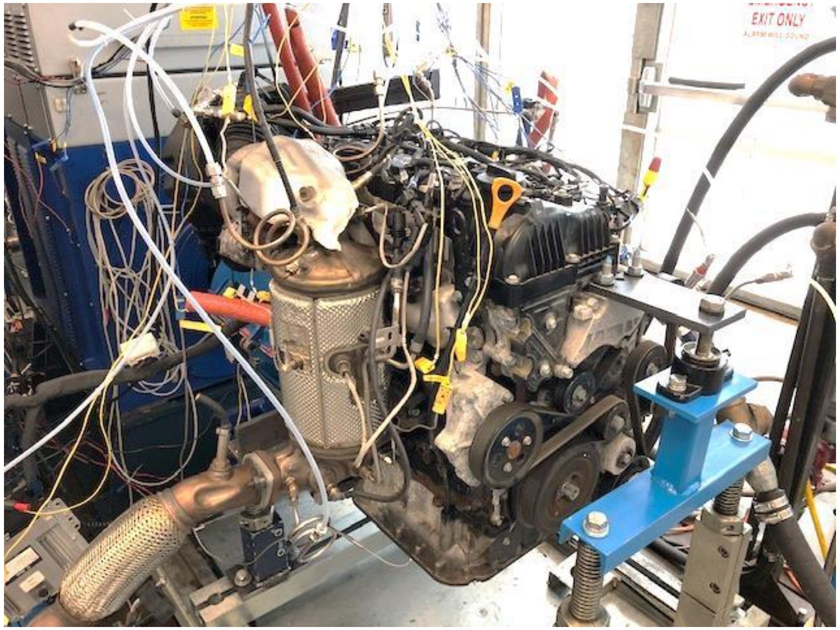




GCI achieved peak BTE 43% @ 2500rpm 15bar BMEP without optimization. SA-LTC peak 34.3%

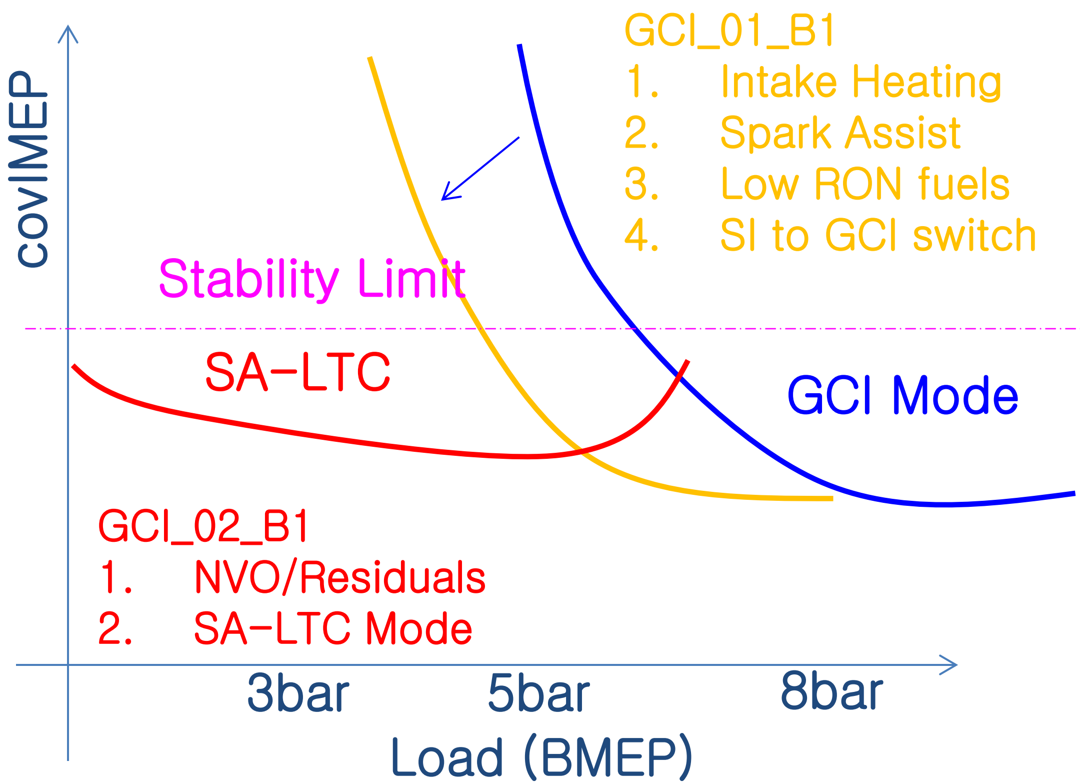
PROPOSED FUTURE RESEARCH

Objective: Low Load GCI Operating Range Extension



From fuel properties we know combustion stability at low temperatures is poor for RON90 fuel

1. Next phase of work will Investigate conventional tactics to improve low load stability
2. Dual CVVD build will enable investigating hot residuals



Test Planning	Timing
GCI_01_B1 Engine 1st Fire	May 2020
GCI Low Load Extension/Tactics	July 2020
SA-LTC Exploration without CVVD	Aug 2020
SI mode to GCI Mode Switch	Sept 2020
GCI and Low RON Fuel	Finalize
GCI_02_B1 CVVD Engine 1st Fire	Finalize
SA-LTC Mode exploration	Next in plan
In-Cylinder Trapped Mass & Residuals estimator	Next in plan

Research Plan adequately designed to address major challenges in operating range extension.

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SUMMARY

M1.1 Technical Specification completed, boundary conditions verified with 1D simulation.
The combustion recipe proposed and multi-mode engine systems procurement under-way.

M1.2 3D CFD Model has been built. Ability to conduct predictive multi-mode injection & combustion & provide feedback to hardware design team. Chemical Mechanism developed for 4 RON fuels

M1.3 Fuels formulation selection and justification of down-selection for GCI testing in process.
-Advanced CI Merit function is delayed but will progress.

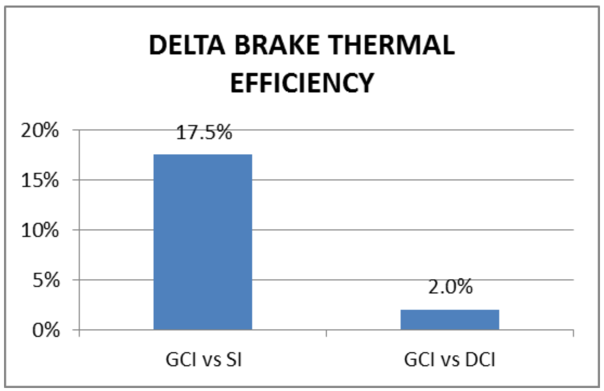
M1.4 Steady-state engine testing of multi-mode (SA-LTC & GCI) BSFC mid to high load demo.

M2.1 Engine Controls: critical year 2 controls task pulled head early into year 1.

- have proven out rapid-proto ECU on dyno in both DCI and GCI modes.

M1.5 Go/No Go: High confidence hardware will meet program targets 150hP@4500rpm & 15% in simulated FTP75 fuel economy over baseline.

- Project is now tracking towards ~20bar BMEP, potentially up to 200hP @ 4500rpm.
- Achieved average of 17.5% BTE improvement over SI (1500 to 3000 rpm)



ACKNOWLEDGE MY PROJECT TEAM MEMBERS

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Lisa Lewis	Purchasing
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Michigan Tech

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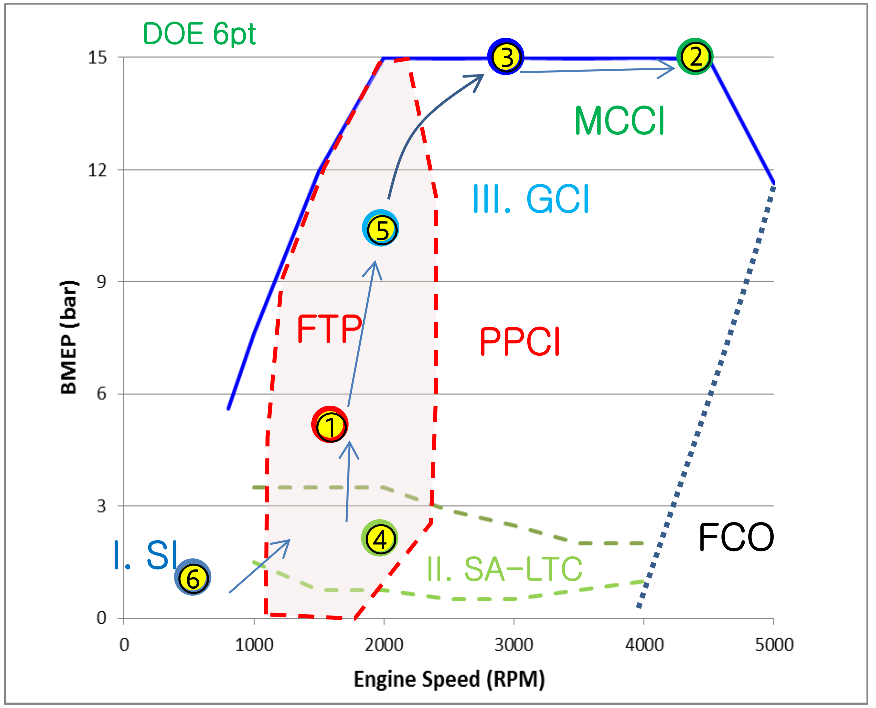
TECHNICAL BACK-UP SLIDES

ENGINE PERFORMANCE TARGETS

	⑥	④	①	⑤	③	②
Engine Speed (rpm)	800	2000	1500	2000	3000	4500
Load (IMEPg) (bar)	2.0	2.6	5.0	10.0	16.6	17.3
Mode	(I) SI	(IIa)	(IIb-III)	(III)	(III)	(III)
BSFC Reduction (%)	5%[1]	20%	15%	20%	18%	17%

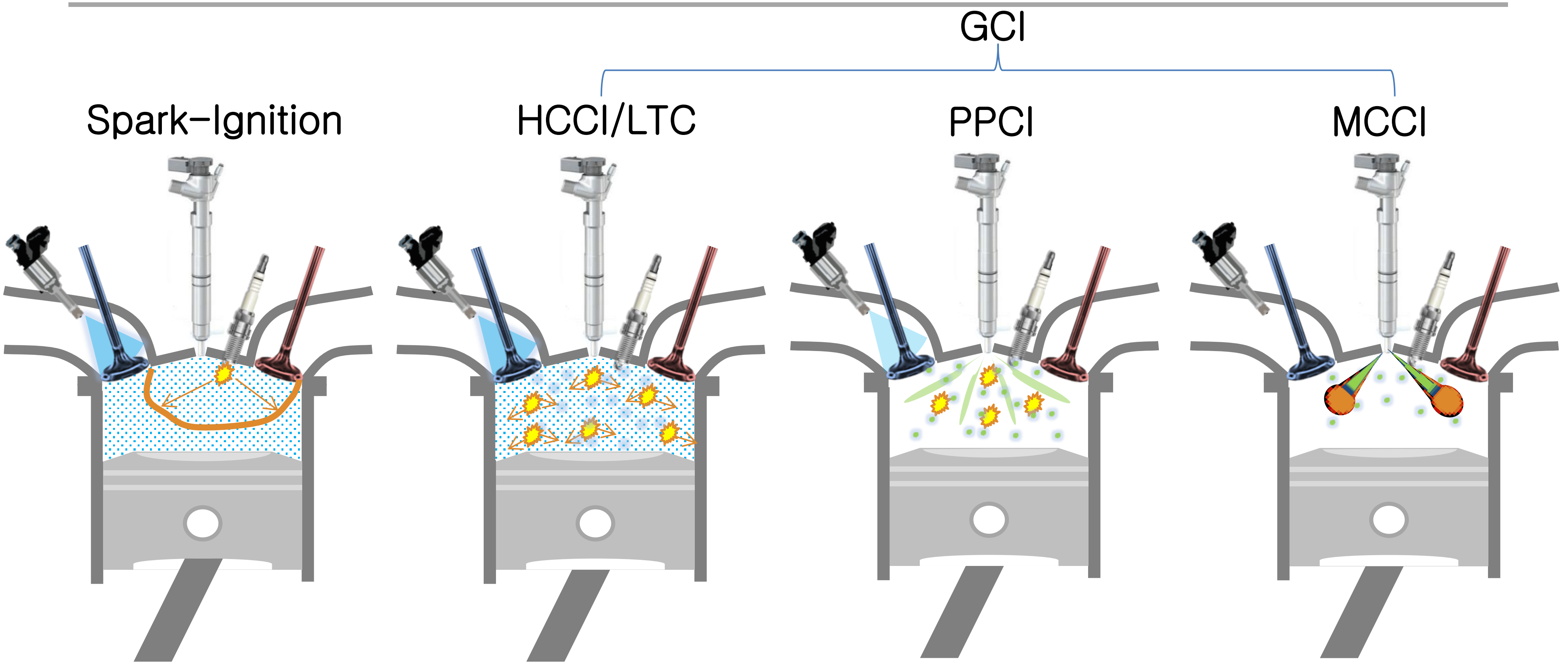
- Cold-Start (I) SI Mode ⑥
  - Retain Spark device for cold-starts.
- Low-Loads (IIa) SA-LTC Mode ④
  - Hot residuals to promote ignition.
- Medium Loads: (IIb-III) GCI mode ① ⑤
  - Lean PPCI, multiple DI inj with high EGR.
- High Loads: (III) GCI ③ ②
  - Late DI MCCI with medium EGR
- Fuel Cut-Off: FCO

<u>Output Targets:</u>
Power: 150hP @4500rpm, 15bar BMEP
Eco: 15-20% reduction over baseline
Pressure Rise: < 8 bar/deg
EO Smoke < 1FSN (assuming GPF used)
EO NOx < 5/gkWhr (assuming SCR used)



Test engine capable of exploring operating range of multiple GCI combustion modes and several fuels

COMBUSTION MODES



Spark-Ignition

Spherical flame front

Propagates outward from spark source

HCCI/LTC

Homogenous mixture

Multiple auto-ignition source

kinetics and residuals

Rapid pressure rise rate

PPCI

Central Rich partially premixed fuel-air mixture

Multiple auto-ignition sources

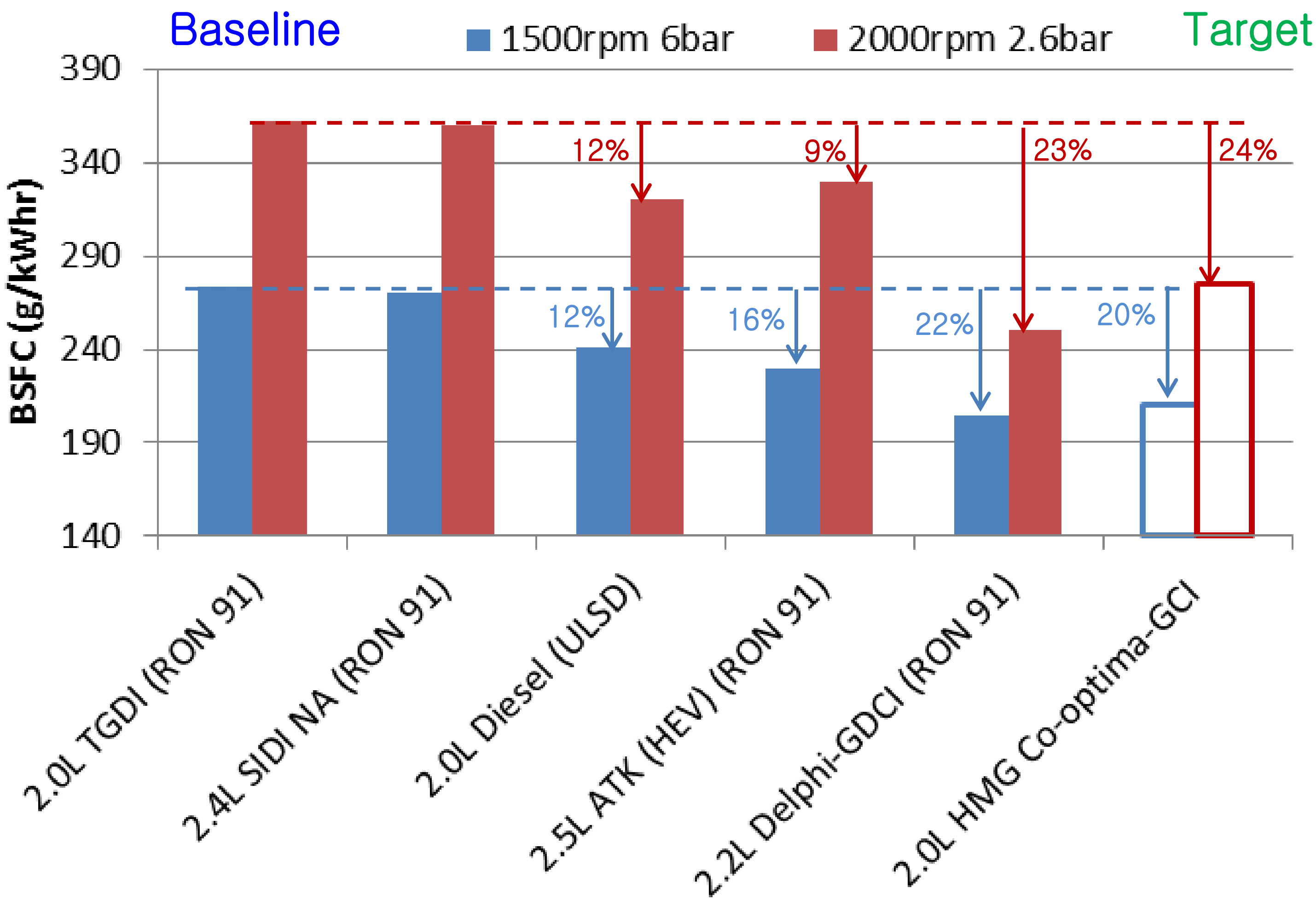
Modulated heat release.

MCCI

Stratified diffusion flame jet
Mixing controlled CI

Spray break-up, mixture form ation, and CI mixture surround ing

FUEL ECONOMY BENCHMARKING



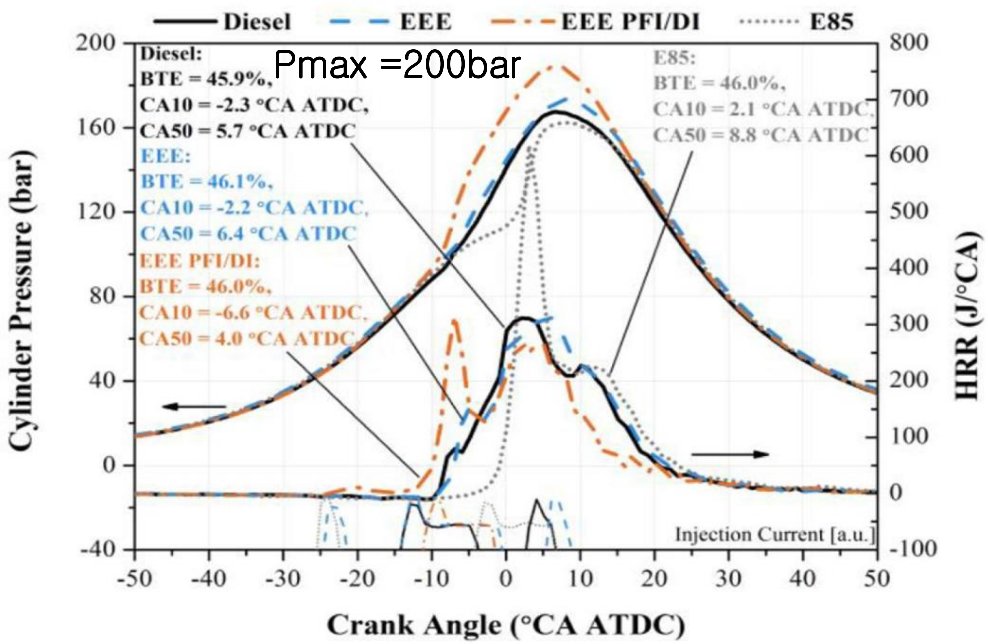
- If we can hit these targets we will be in a good position to achieve our objectives for this project

REFERENCES: MIXING CONTROLLED COMPRESSION IGNITION

12.4 L I6 Heavy Duty Diesel Pcyls and HRR for diesel and E85 gasoline baseline and peak BTE conditions of EEE gasoline.

Cylinders	6
CR	17
rpm	1050
IMEP [bar]	14
P Intake [bar]	2.3
EGR %	0

Injection Strategies			
SOI (°CA ATDC)	EEE	EEE PF I/DI	E85
Main	-16	-12	-6
PFI	-	-550	-550
Pilot	-27	-	-27.5
Post	4	-	-



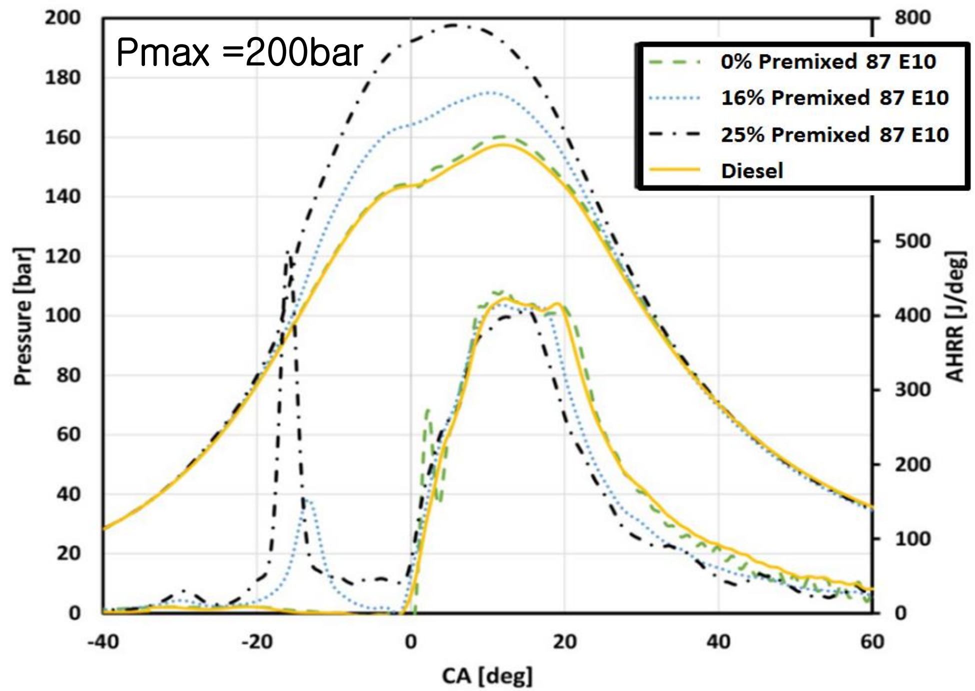
Wang B, Pamminger M, Wallner T. Optimizing Thermal Efficiency of a Multi-Cylinder Heavy Duty Engine with E85 Gasoline Compression Ignition. SAE Technical Paper; 2019.

2.5 L SCTE GCI Engine Test
Premixed fuel: direct-injection during valve overlap period (350 dBTDC)

Cylinders	1
CR	16.4
rpm	1200
IMEP [bar]	20
P Intake [bar]	2.85
EGR %	0

Single injection, near top dead center

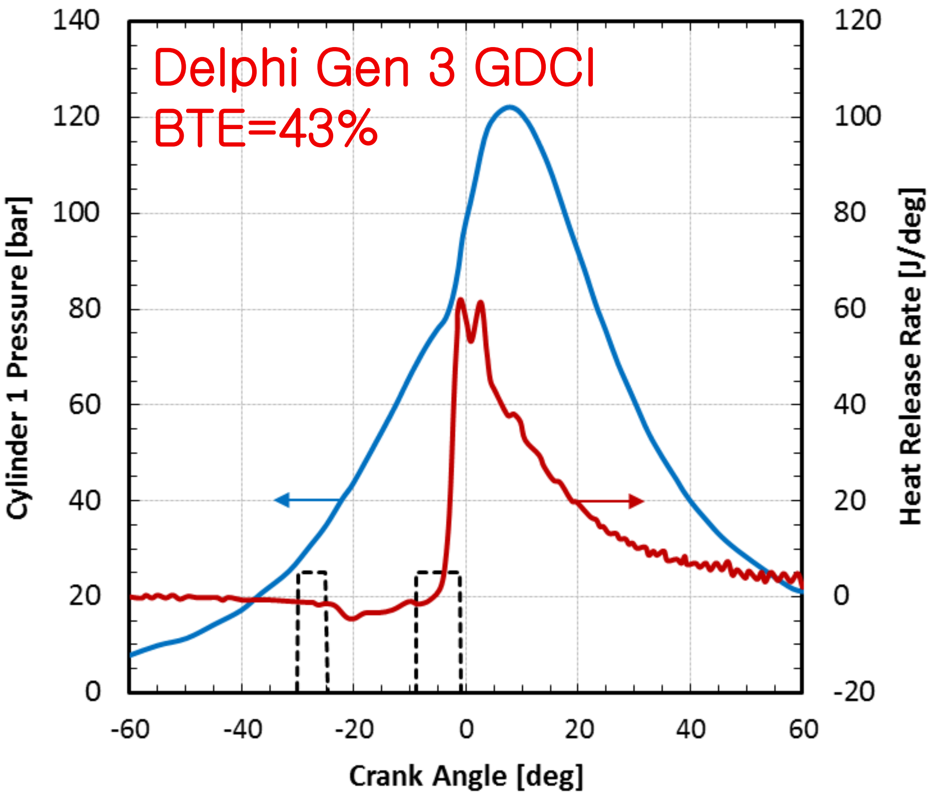
20 bar BMEP

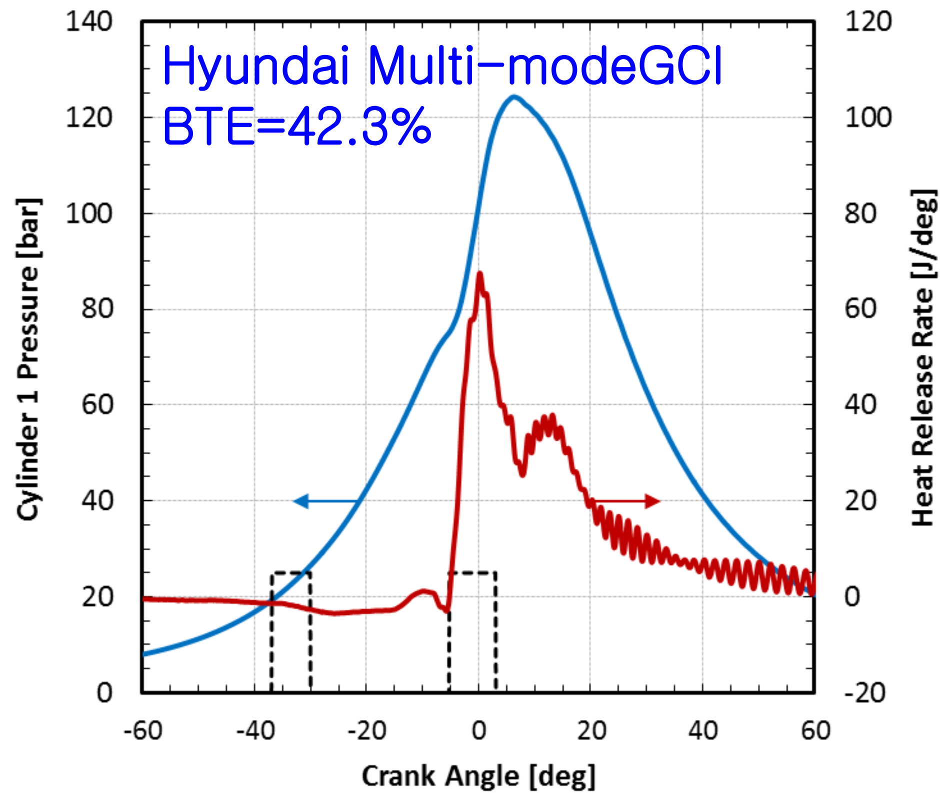


Paz J, Staaden D, Kokjohn S. Gasoline compression ignition operation of a heavy-duty engine at high load. SAE Technical Paper; 2018 .

COMBUSTION MODE BENCHMARKING

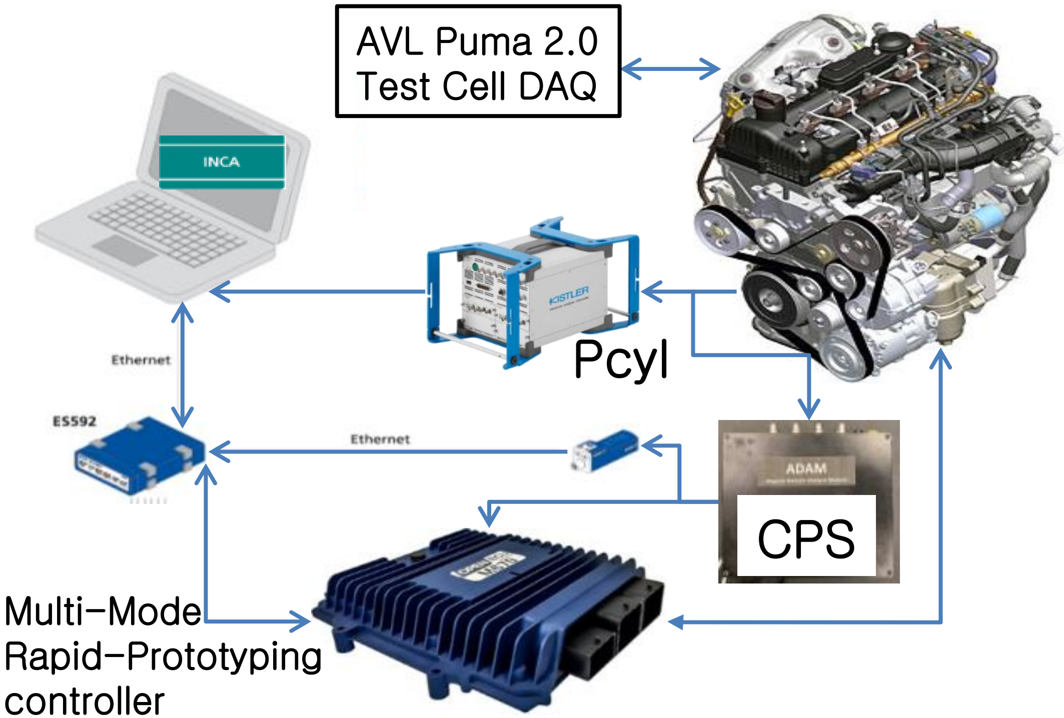
1750rpm 12 bar BMEP – Delphi Gen 3 GDCI vs Hyundai Benchmarking



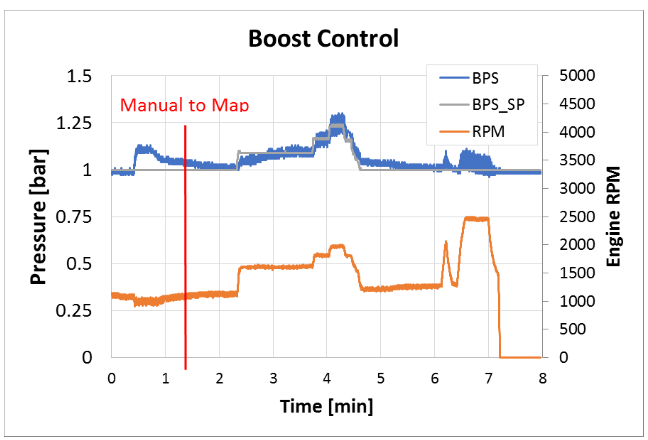


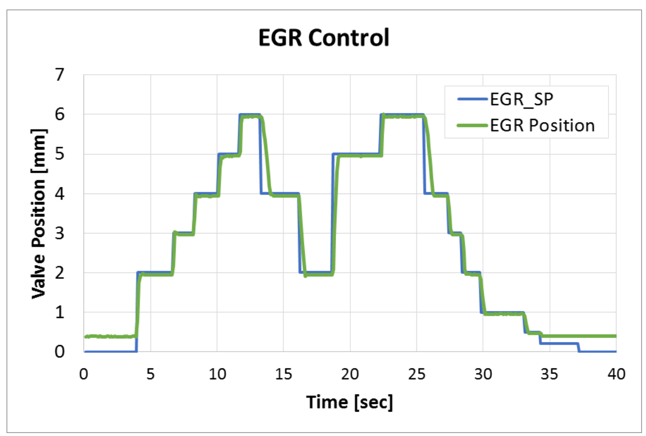
Hyundai Multi-mode GCI achieved almost identical brake thermal efficiency as Delphi Gen 3 GDCI.

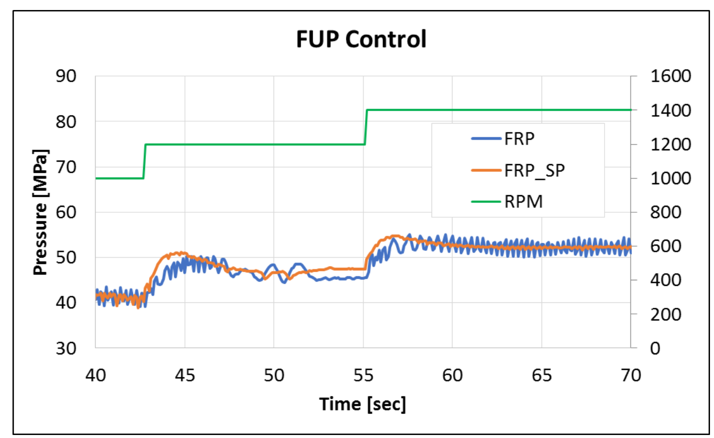
ADVANCED ENGINE CONTROLS



Actuator / Sensor		Status
Pedal Control	green	Pedal→Torque request achieved
Crank/Cam Position Sensor	green	Crank/Cam synchronicity achieved
Mass Airflow Sensor	yellow	MAF reads data, integration next
Air Control Valve	green	Actuation possible
Variable Swirl Valve	yellow	Model & calibration integration needed
Manifold Absolute Pressure	green	Setpoint & feedback control achieved
Fuel Rail Pressure	green	Fuel pressure control achieved
Fuel Metering Valve	green	FMV control achieved
PFI & DI Injectors	green	SOI & quantity control achieved
E-Variable Geometry Turbo	green	Boost pressure control achieved
EGR Valve	green	EGR manual control achieved





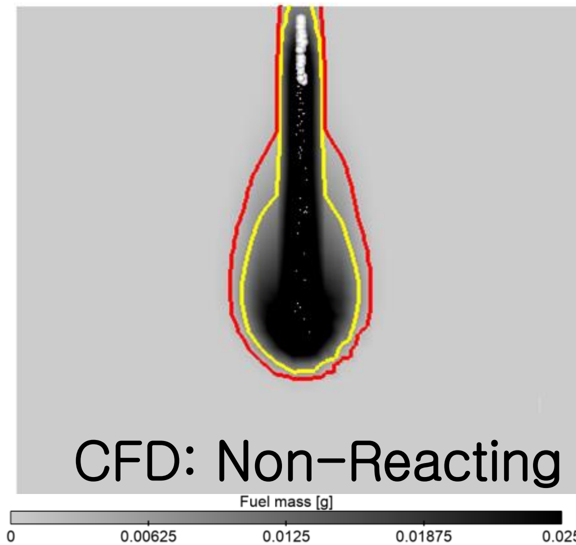


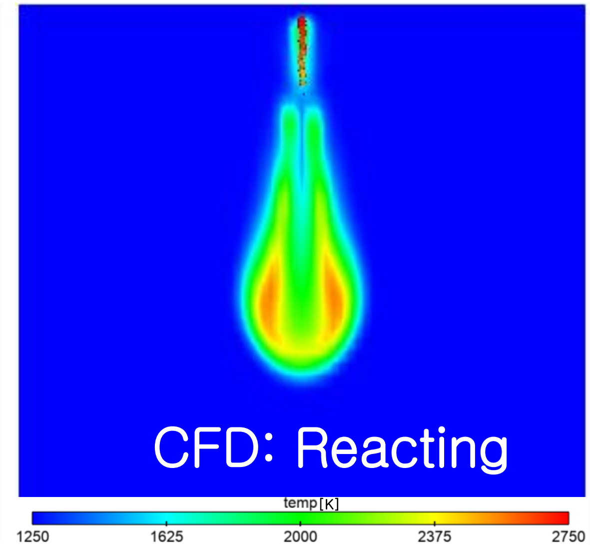
M2.1: 1st Generation Multi-Mode Rapid-Prototyping controller has been developed & commissioned

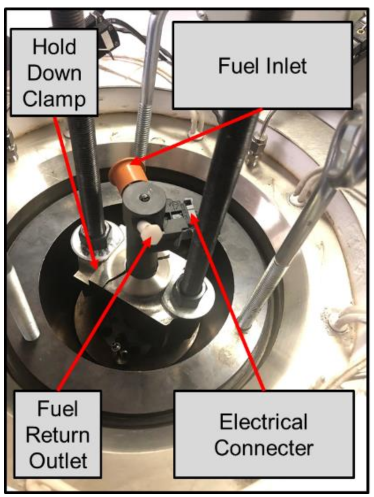
DIRECT INJECTOR SPRAY CHARACTERIZATION

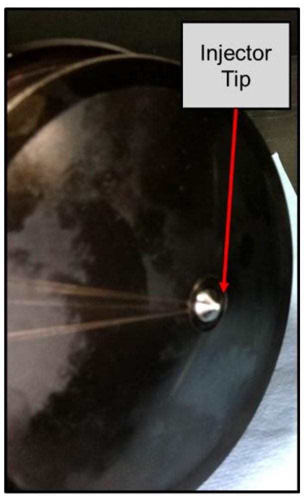
Non-reacting & reacting conditions
- Fuel reactivity (RON 63-90)
- Injection pressure (200-1000bar)
- Charge density (2-40 kg/m3)
- Charge temperature (400-1200K)
- EGR (10%-35%)

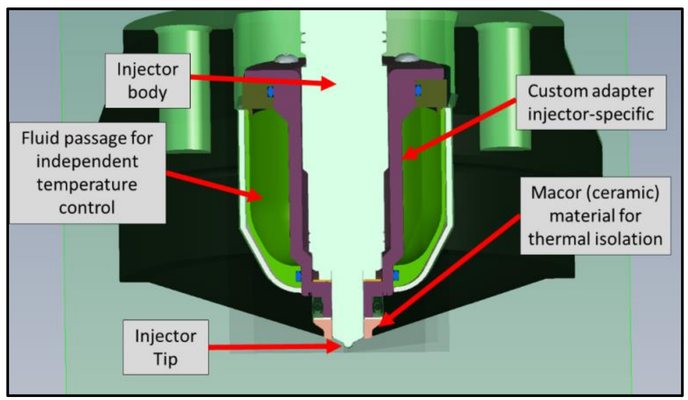
Spray characteristics
- Liquid/vapor penetration
- Cone angle
- Ignition delay
- Heat release rate, etc.











- CFD Model setup for CV Chamber
- Ready for DI injector to be delivered and start spray experiments

PROJECT TEAM


Phil Zoldak, MS-ME
Principal Investigator
Engine Dev & Test
20 years exp

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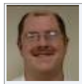
Comb Dev / Design /Analysis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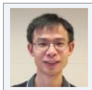
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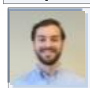
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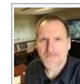
Robert Wagner, PhD
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Acknowledgements
Kevin Stork
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Accounting

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Sara Shaw-Legal
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